Visualization and Quantification of Rotor Tip Vortex in Helicopter Flows

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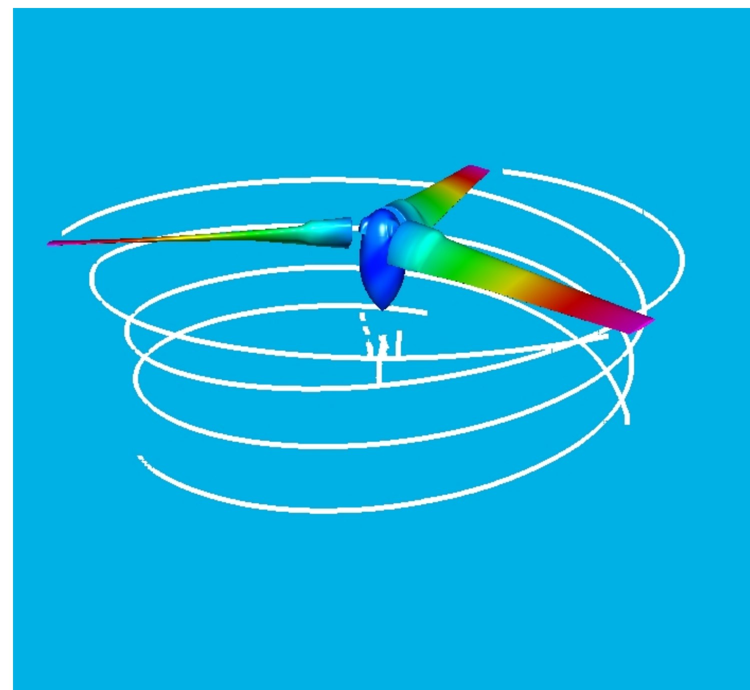
Kao, Ahmad & Holst, AIAA SciTech 2015, Kissimmee, FL   AIAA-2015-1369

Overview

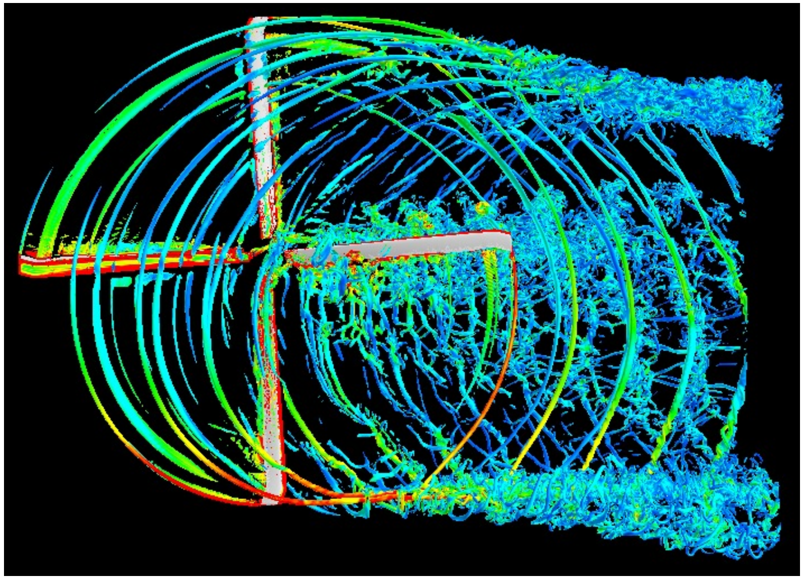
- Motivation
- Approach
- Results
- Conclusions



Motivation

Visualization of rotorcraft flow fields is challenging due to flow phenomena from complex interactional aerodynamics:

- **Blade-vortex interactions (BVI)**
- **Vortex pairing**
- **Vortex-wake interactions**
- **Vortex breakdown**
- **Interaction of various flow features with the fuselage**

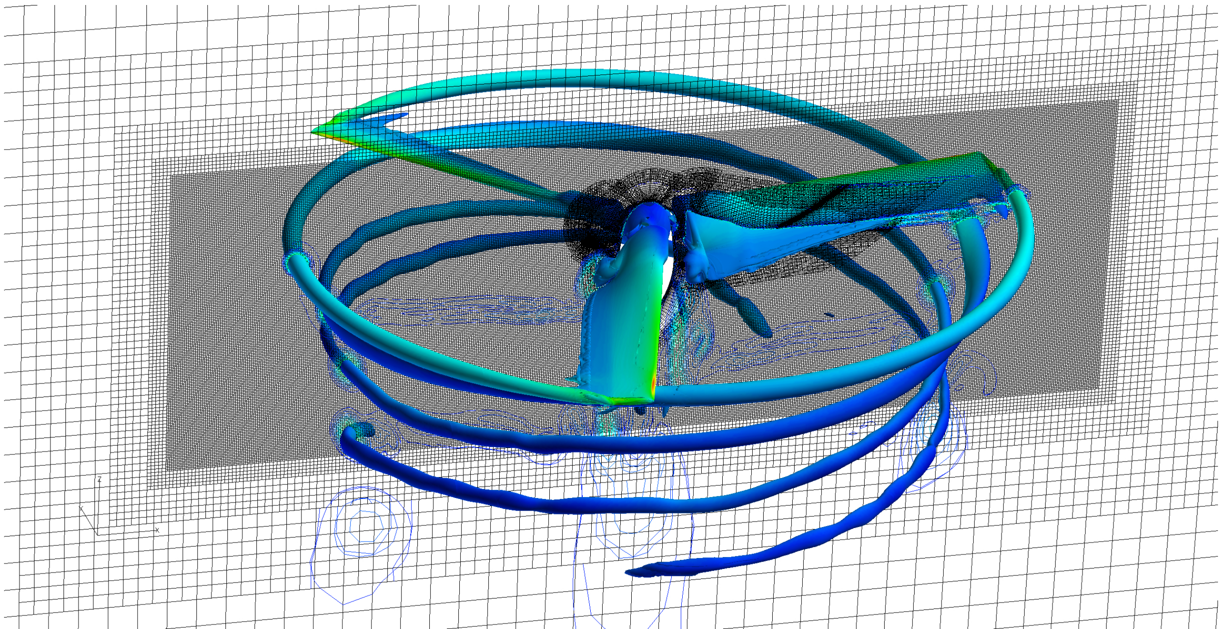


Vortices: Q-criterion iso-surfaces (UH-60A Rotor Blades, M_{tip} = 0.65, μ = 0.15)

Sikorsky UH-60 Blackhawk

Objectives

- Develop an automated approach to quantify vortex core strength from numerical flow simulations
- Determine flow field regions to perform vortex core profiling
- Display the extracted vortex core radii using a new color map scheme

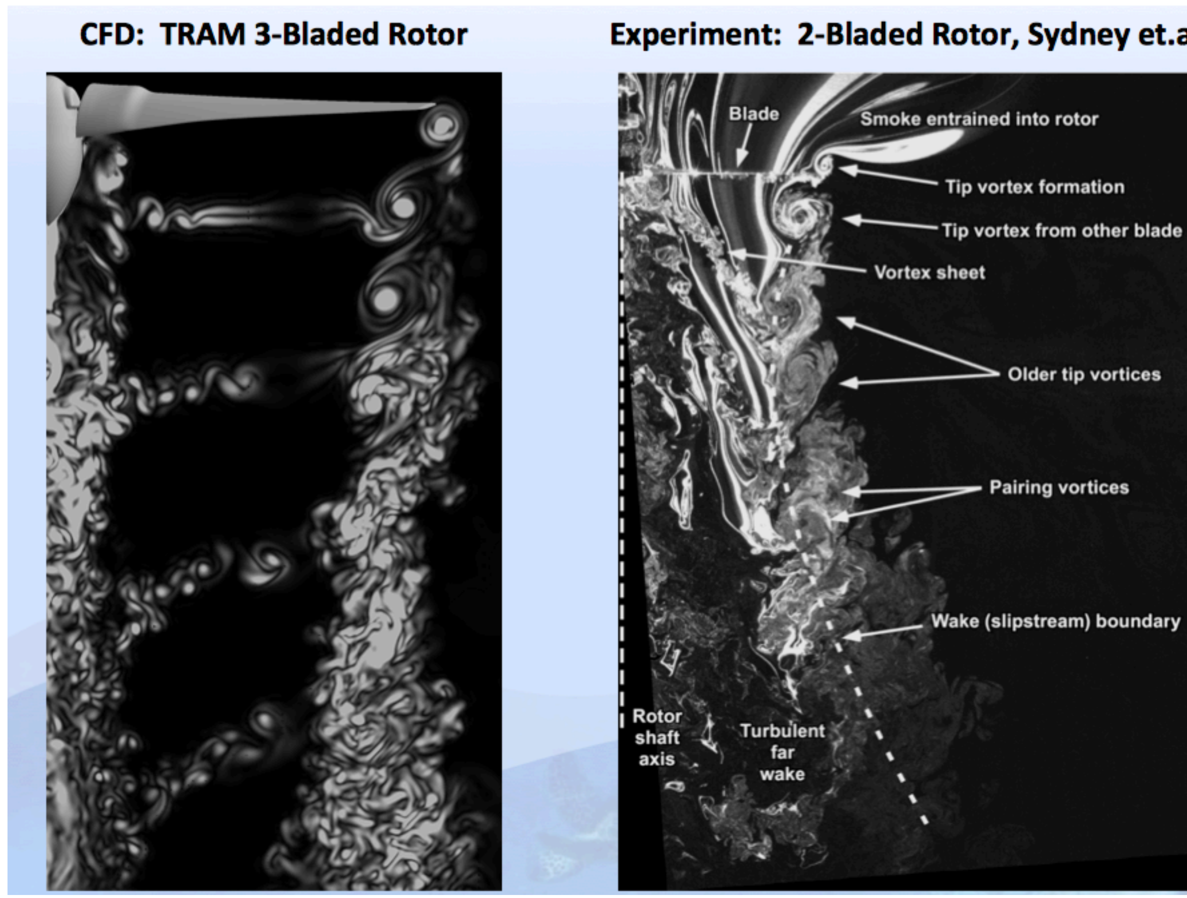


Comparison with Experimental Data

Additional visualization challenges arise when attempting to compare CFD results with experimental data

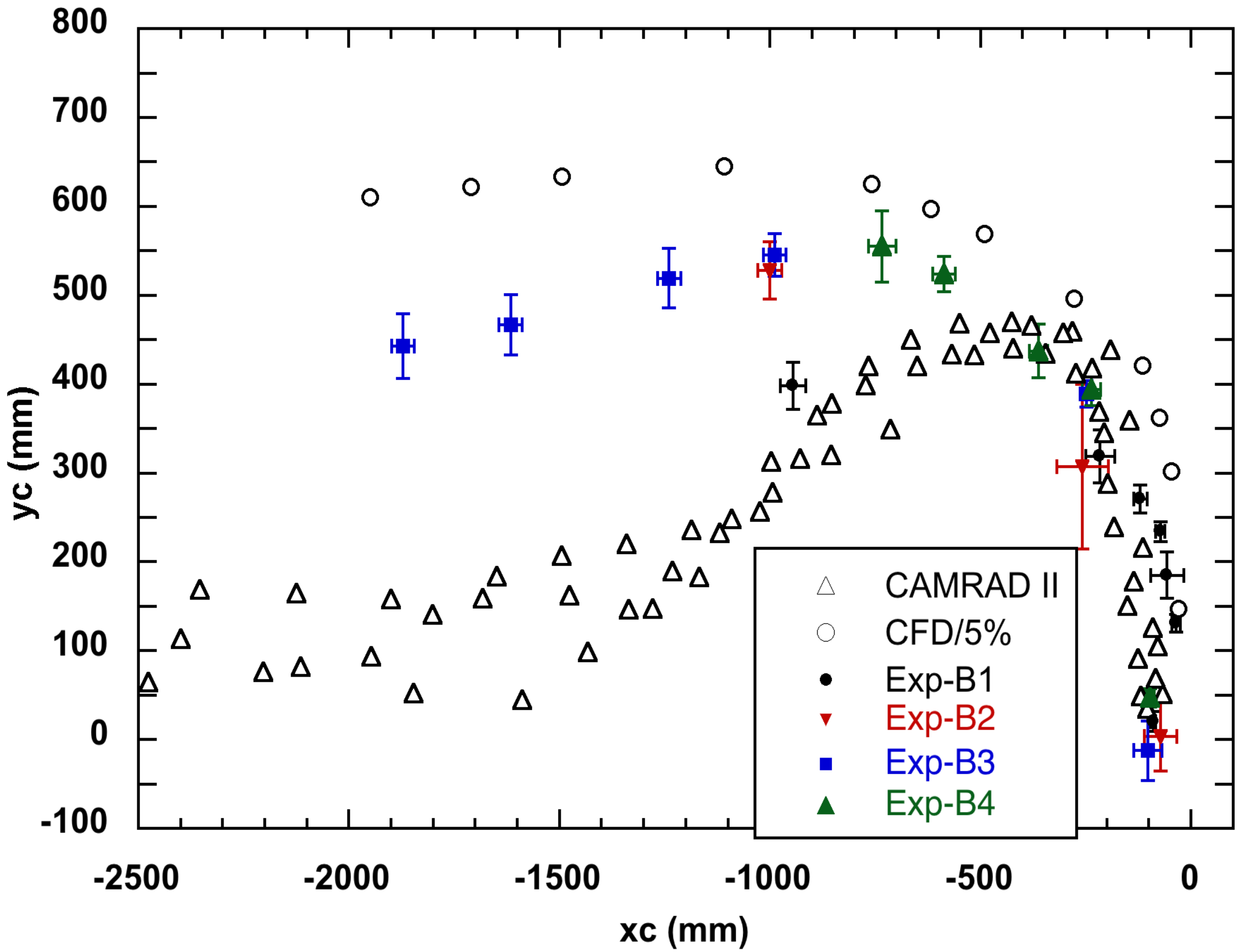
It is important to predict:

- **Blade tip vortex position**
- **Vortex core radius**
- **Vortex core growth rate and wandering**



[Chaderjian ’15]

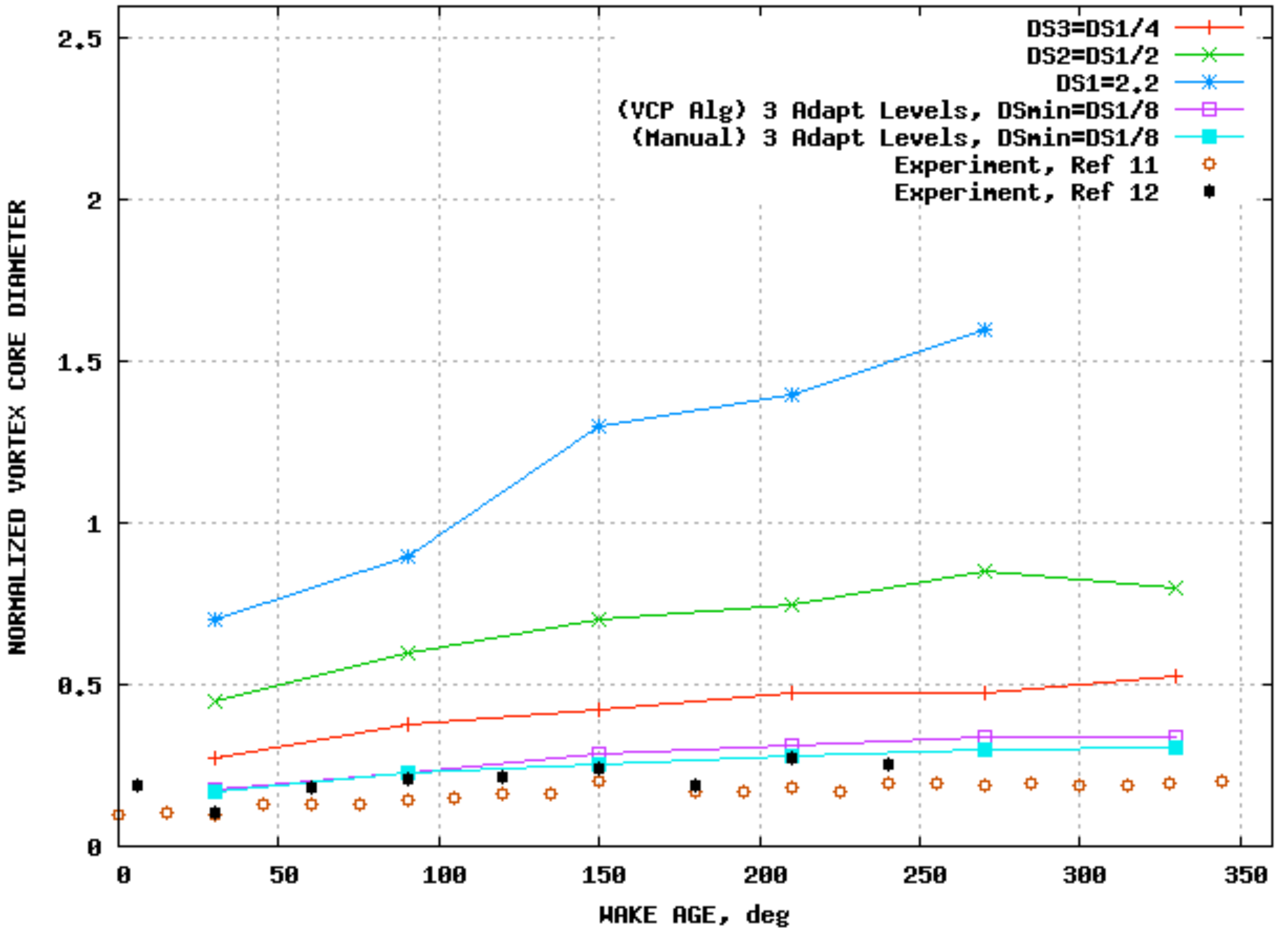
Blade Tip Vortex Position



It often requires some effort to generate each data point

Predicted and measured tip vortex trajectories for Run 73. Error bars represent ±one standard deviation. CFD/5%: refers to fine grid with L1 spacing of 5%Ctip. [Ahmad, Yamauchi & Kao, AIAA 2013]

Blade Tip Vortex Core Diameter Growth



Core diameter at each wake age is often calculated manually

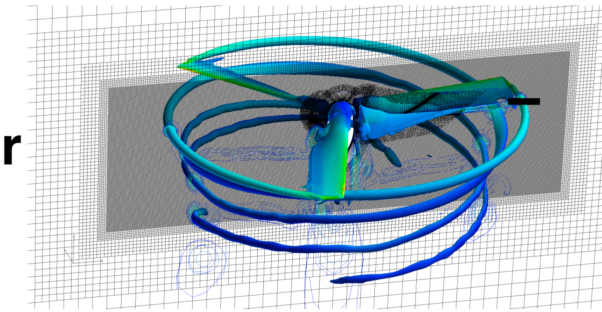
Normalized vortex-core diameter growth with wake age using uniform background grid refinement and solution-adapted results with imbedded Cartesian grids ($\Delta s_2=\Delta s_1/2$, $\Delta s_3=\Delta s_1/4$, and $\Delta s_4=\Delta s_1/8$). [Kao & Chaderjian AIAA 2010]

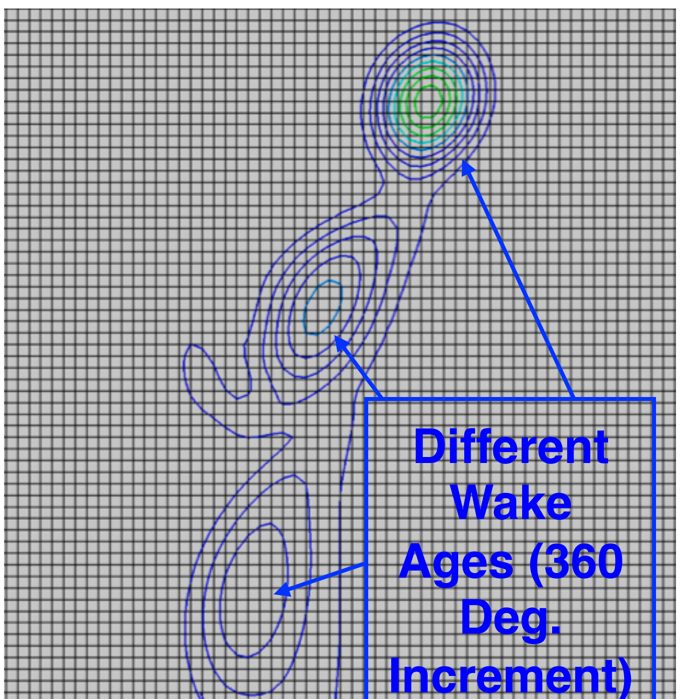
Manual Approach

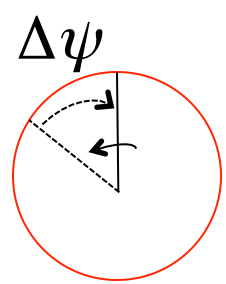
An ad hoc process for vortex core analysis:

- Locate vortex core center
- Determine a reference line through the vortex-core center
- Plot the cross-flow velocity component perpendicular to the reference line
- Manually calculate the vortex core diameter
- Repeat the process for several wake ages

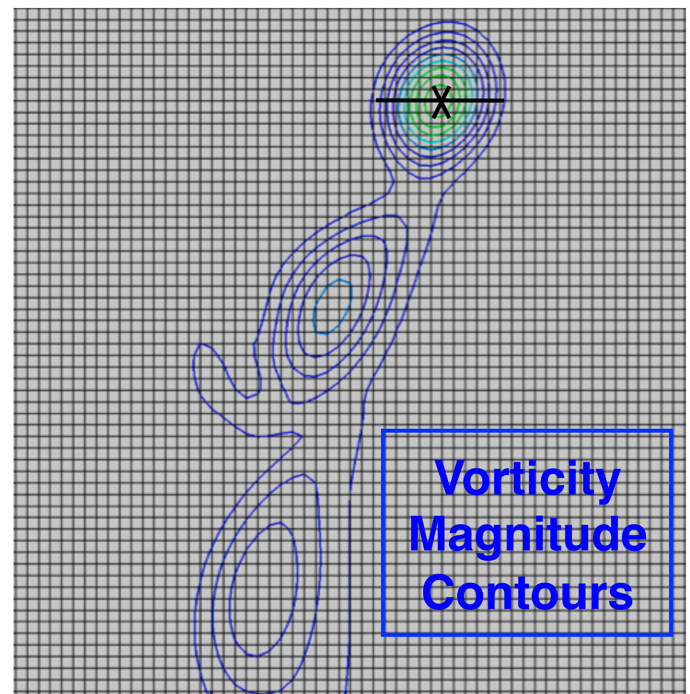
➢ Tedious and prone to user error



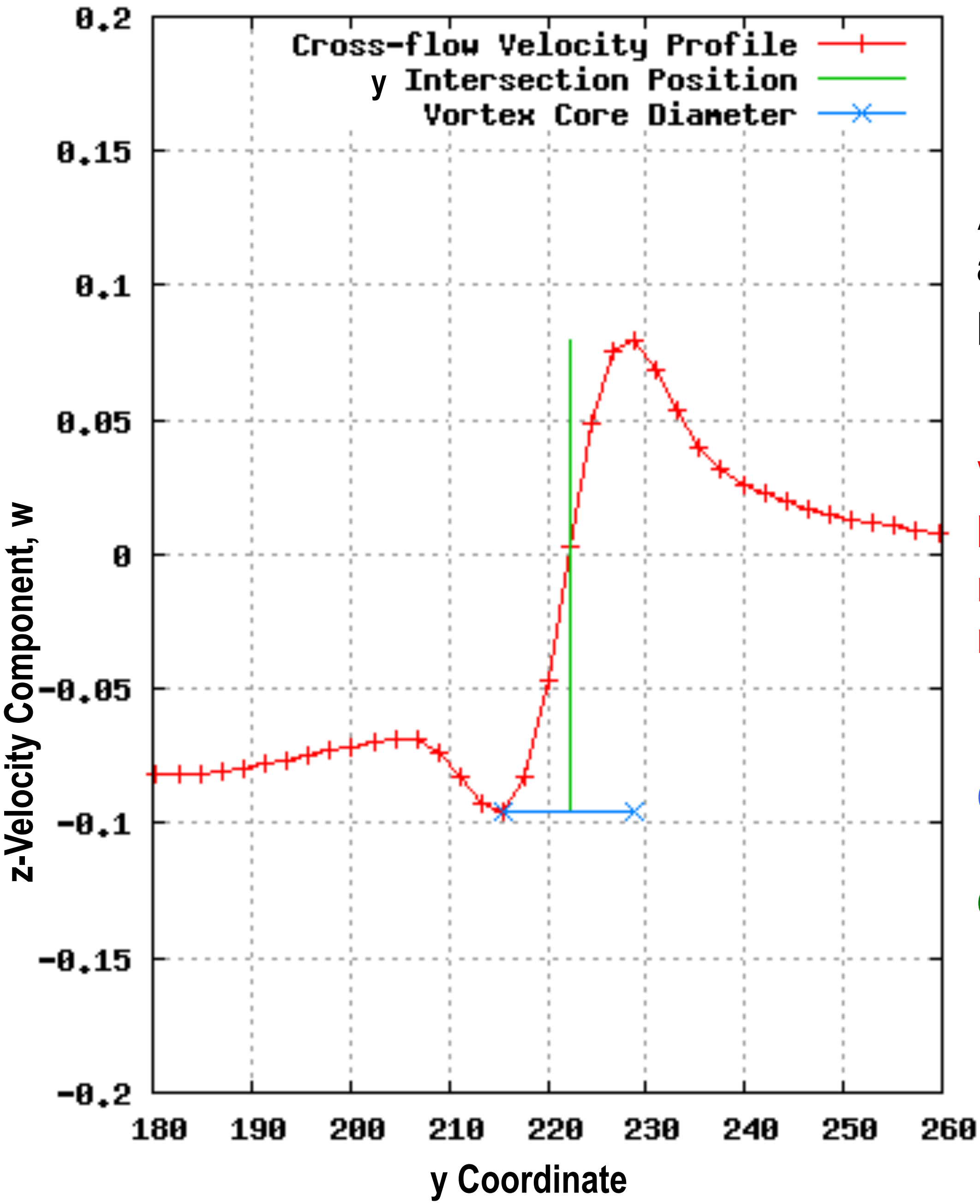




Wake Age



Vortex Core Diameter



A cross-flow velocity profile plot along the y axis (for x=0 cutting plane)

Vortex core diameter is the distance between the local minimum and maximum cross-flow velocity magnitudes

Cyan line: Vortex core diameter

Green line: Vortex core center

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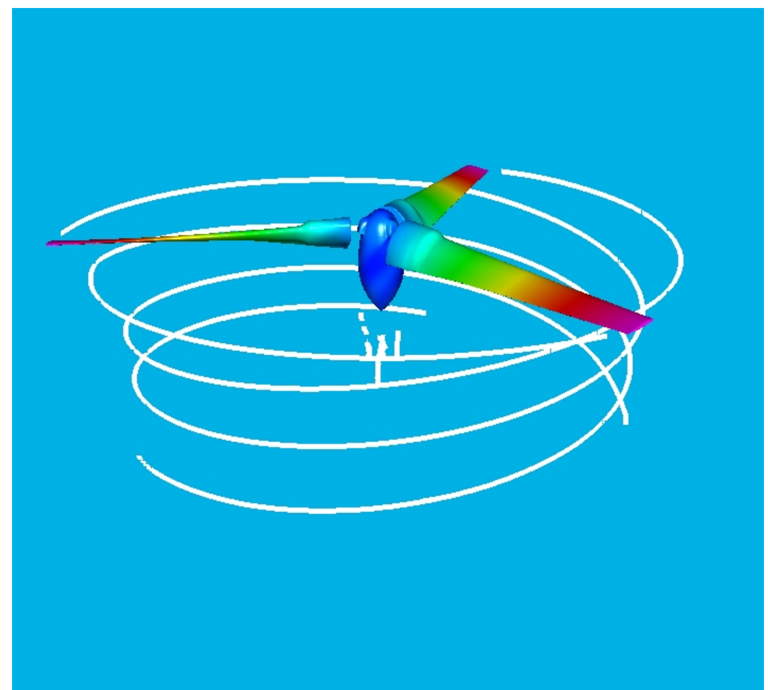
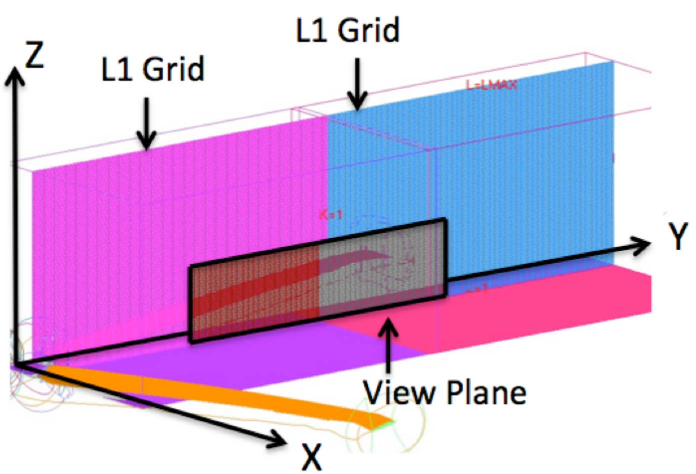


Proposed Approach

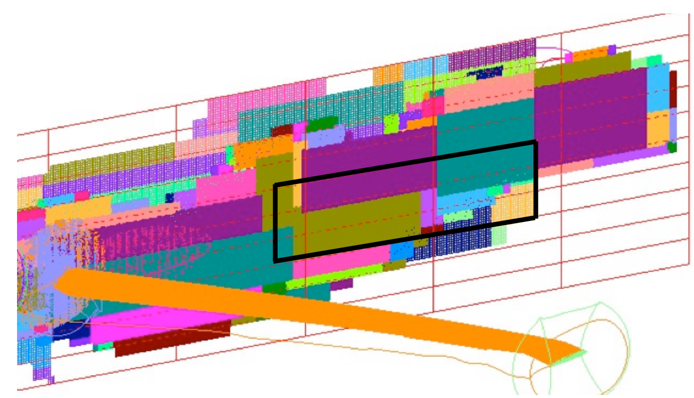
1. Construct a *view plane* to represent the experimental Particle Image Velocimetry (PIV) plane using a Cartesian grid

2. Automatically extract vortex core strengths on the view plane

3. Display the captured vortex core strengths as color-mapped contours on the view plane



View plane spans across two Level 1 (L1) off-body grids



View plane spans across many off-body grids in an AMR grid case

Automatic Vortex Core Radius Extraction

1. Construct a *view plane* to represent the experimental Particle Image Velocimetry (PIV) plane using a Cartesian grid

2. **Automatically extract vortex core strengths on the view plane**

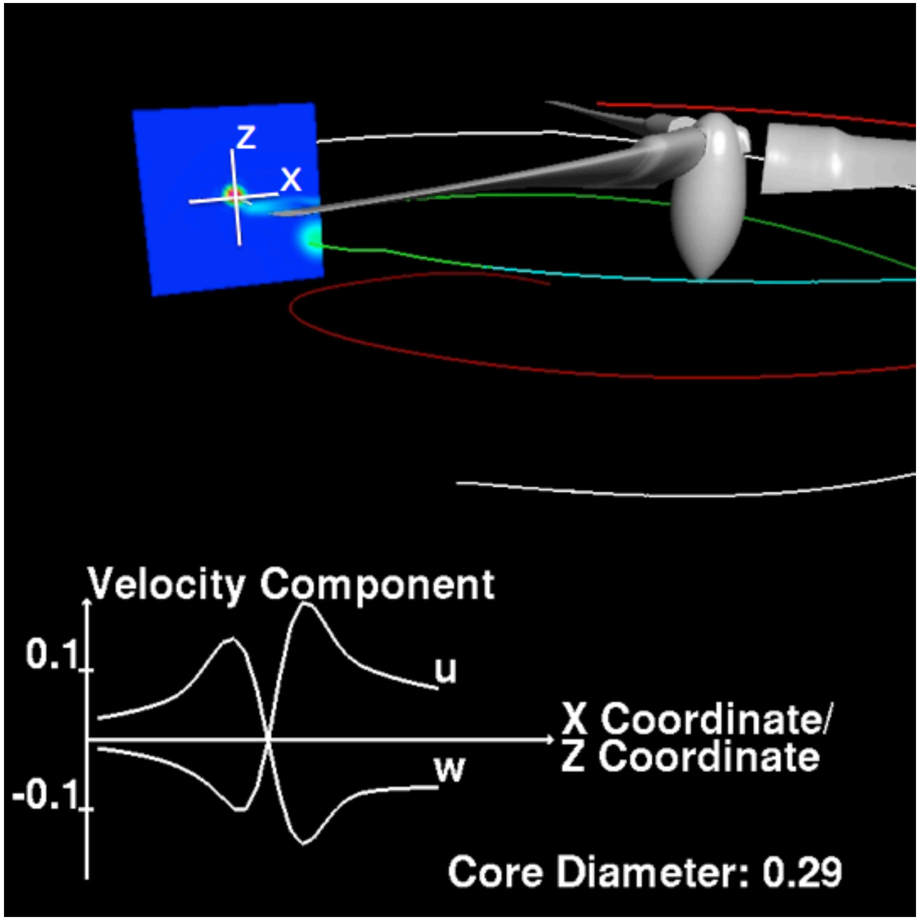
   - **Automatically select a set of grid points on the view plane to extract the vortex core radius**

   - **For each selected grid point *P*, compute the cross-flow velocity component for two orthogonal axes with a common origin at *P***

   - **The final vortex radius is the average of the core radii calculated from the two cross-flow velocity profiles**

3. Display the captured vortex core strengths as color-mapped contours on the view plane

Cross-flow Velocity Component Profiles



Two profiles:

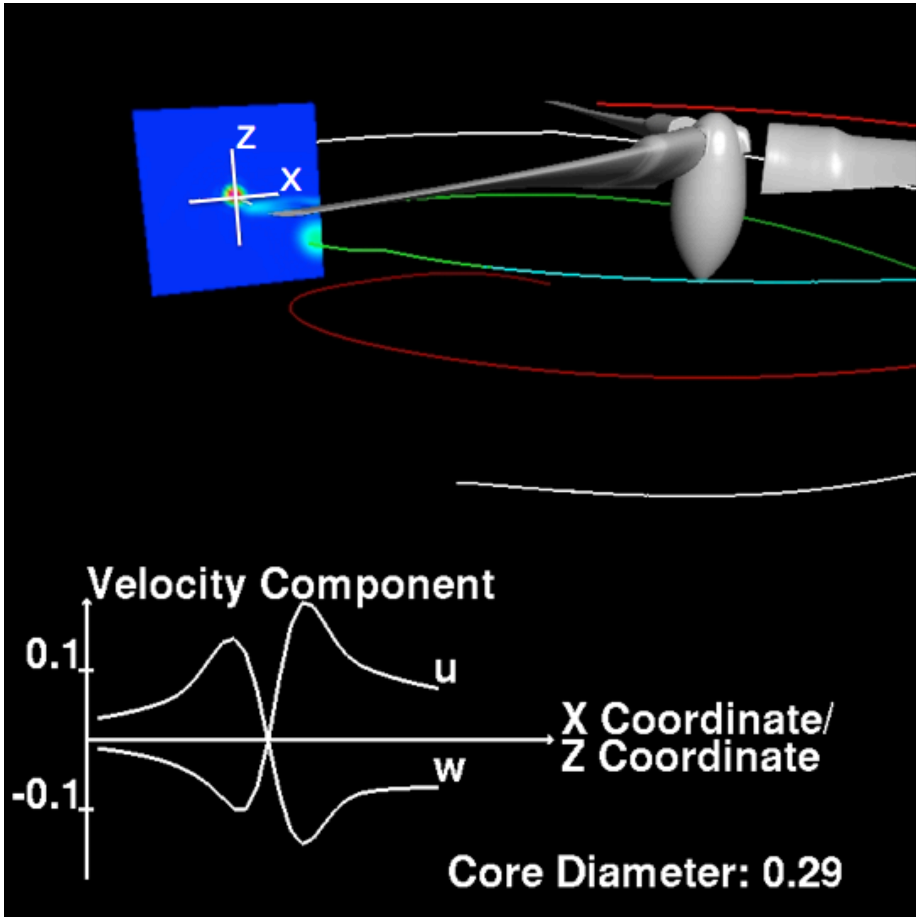
- **w component along the X axis**
- **u component along the Z axis**

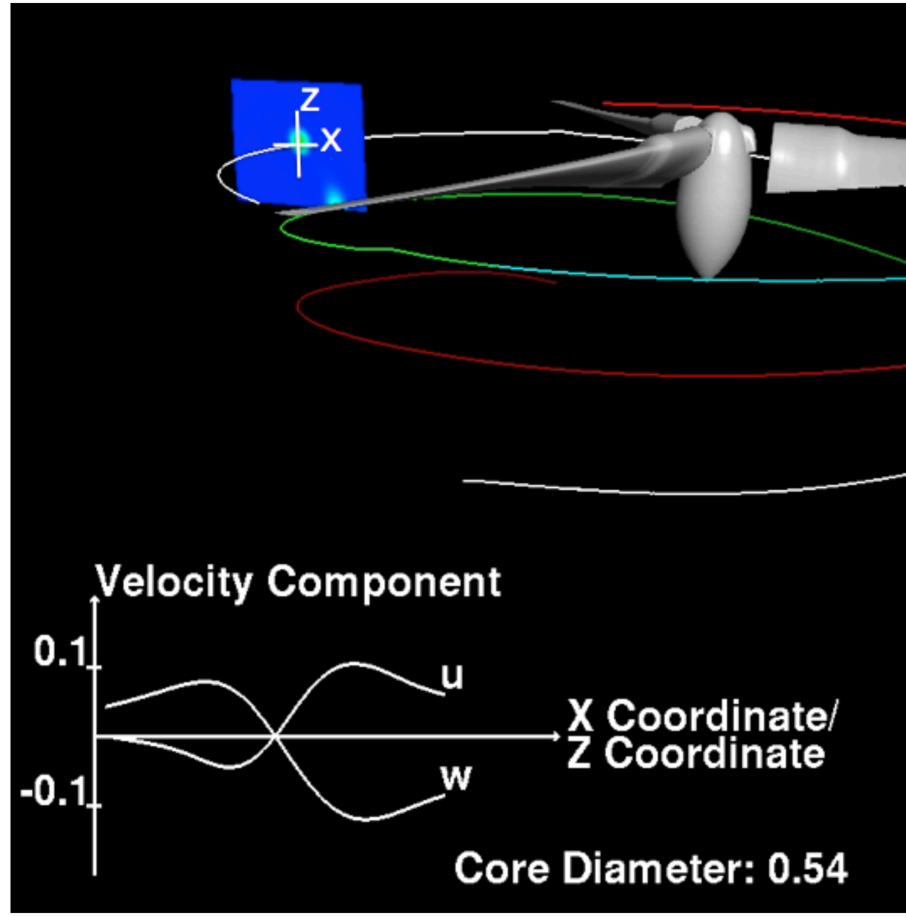
The core diameter is the average of the core diameters from the two profiles

Cross-flow velocity component profiling at one position along a vortex line.

The vortex core diameter is 0.29 inches.

Cross-flow Velocity Component Profiles



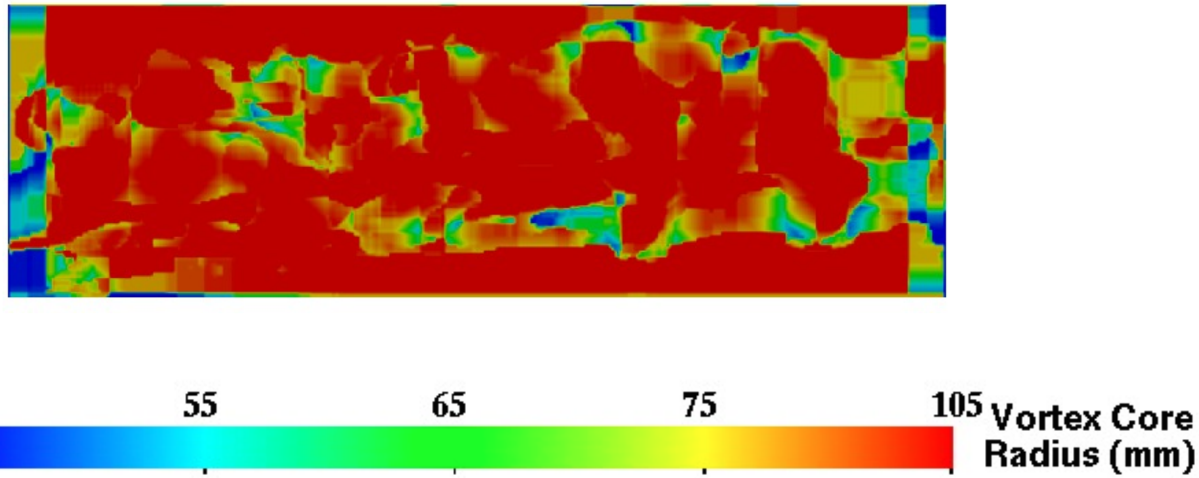


Cross-flow velocity component profiling at two positions along a vortex line.

The vortex core diameter dissipates quickly from 0.29 to 0.54 after ~1/16 blade revolution.

Grid Point Selection Criterion - #1

- Select <u>all grid points </u>in the view plane
- Perform vortex core profiling at the selected grid points
- Display the core radius as a contour plot

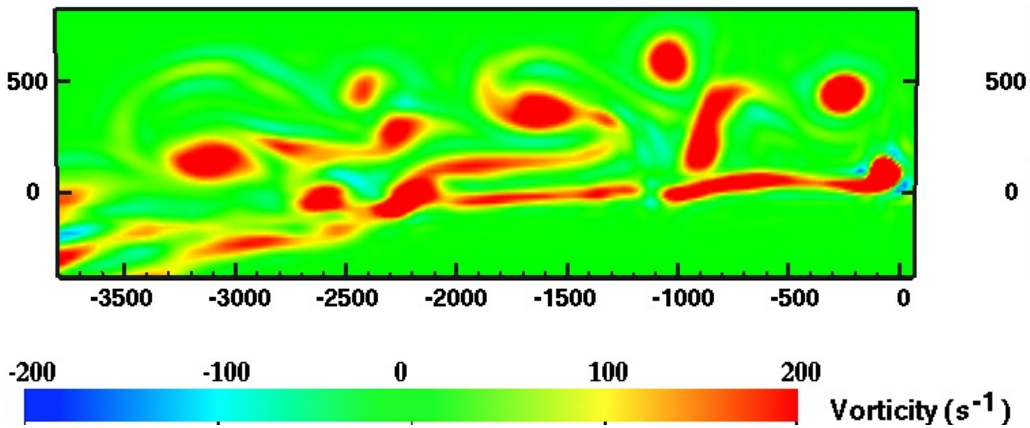


Vortex core radius contour on the view plane

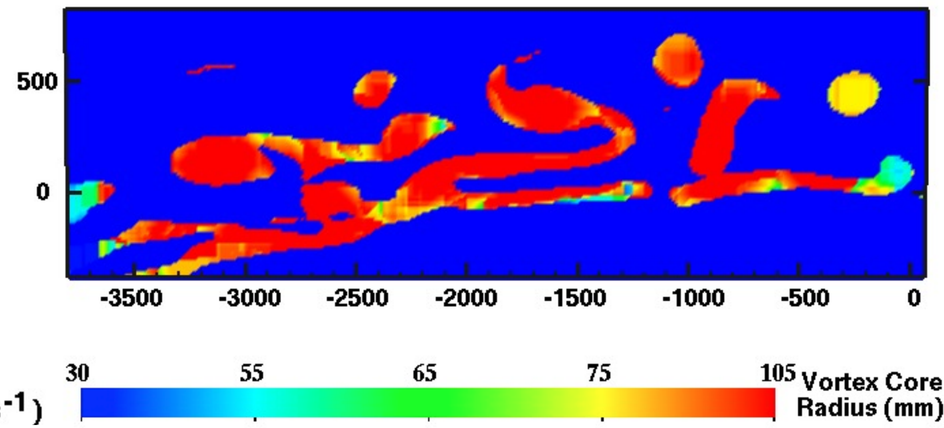
➢ **Results difficult to interpret**

Grid Point Selection Criterion - #2

- Select grid points where vorticity magnitude is above a threshold value
- Perform vortex core profiling at the selected grid points
- Display the core radius as a contour plot



Vorticity magnitude contours



Vortex core radius contours

The core radii are calculated for all grids points where the vorticity magnitude is greater than 64 s^{-1}.

- ➢ **Sensitive to user-specified threshold value**
- ➢ **Some profiling locations are not near to a vortex core**

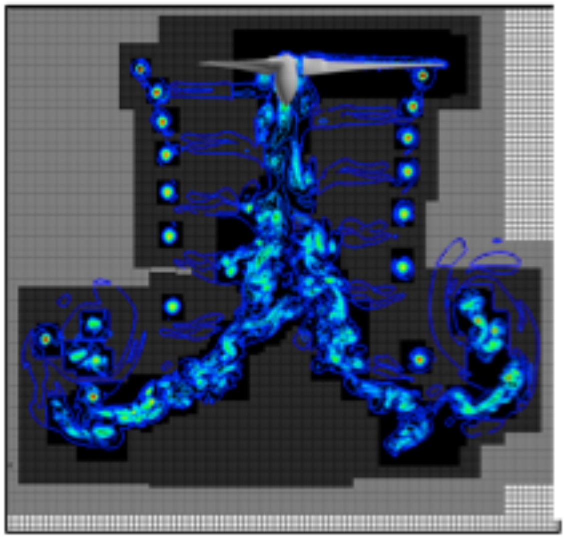
Scaled Q Criterion

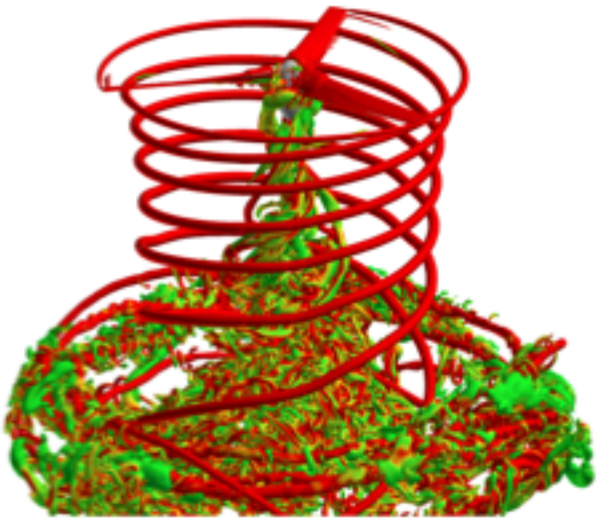
The scaled Q criterion is Q criterion normalized by shear strain.

A threshold of unity is an effective marker of the vortex boundary (Kamkar et al., J. of Computational Physics 2011).

$$Q = \frac{1}{2}\left(\|\Omega\|^2 - \|S\|^2 \right)$$

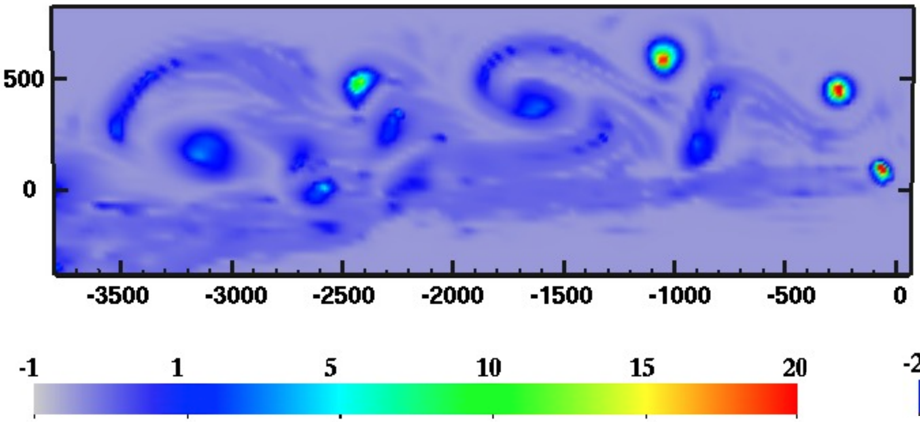
$$Q_s = \frac{1}{2}\left(\frac{\|\Omega\|^2}{\|S\|^2} - 1 \right)$$



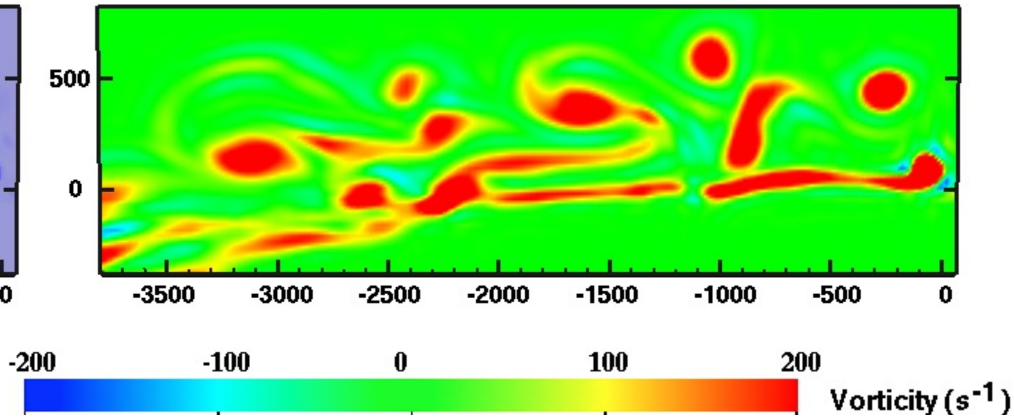


Useful in AMR methods.
Refine whenever Qs > 1 [Wissink]

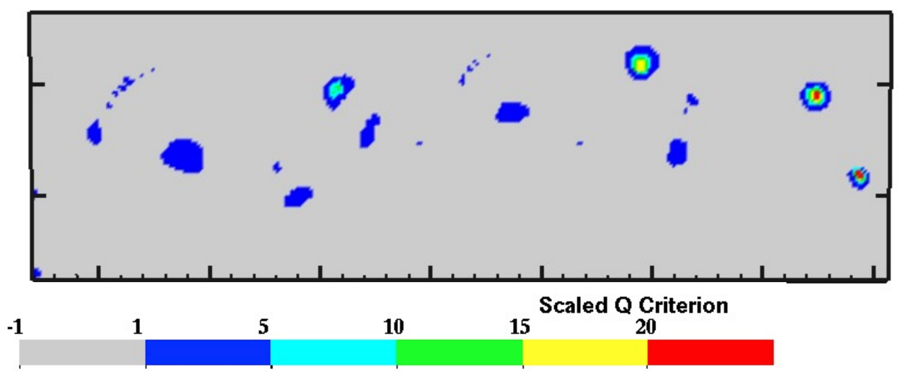
Scaled Q Criterion Versus Vorticity Magnitude



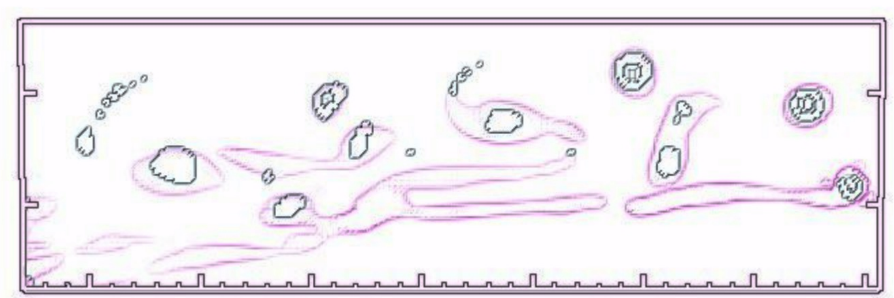
Scaled Q criterion contours (Continuous color map)



Vorticity magnitude contours



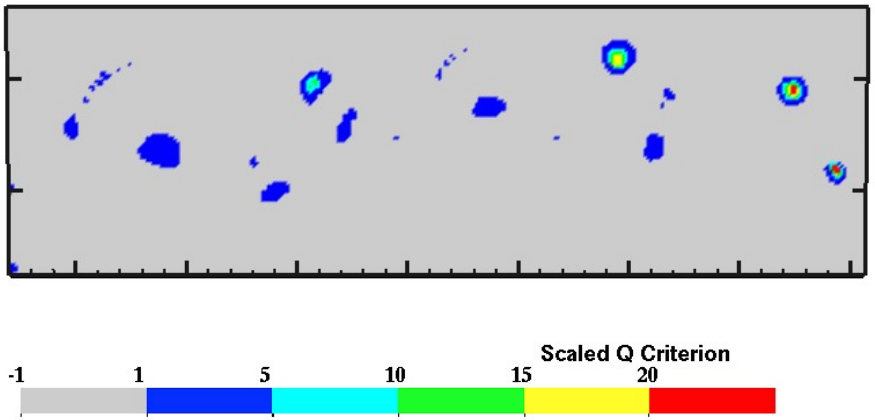
Scaled Q criterion contours (Banded color map)



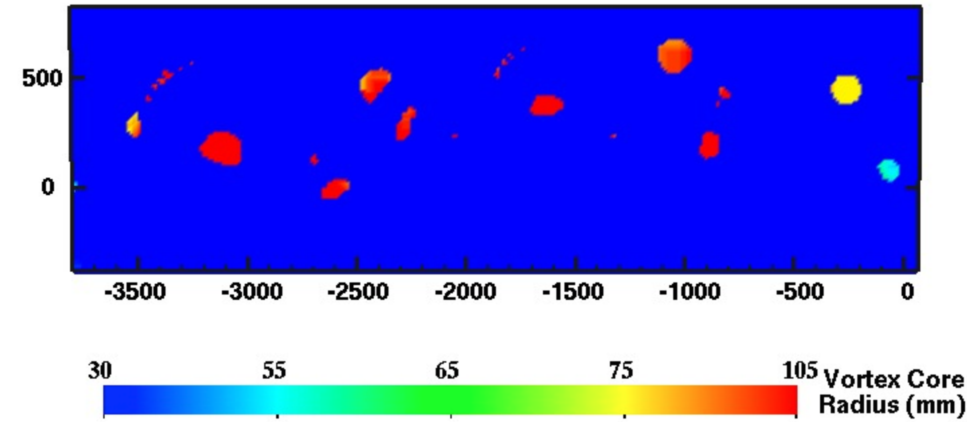
Scaled Q criterion contours (black)
Vorticity magnitude contours (magenta)

Grid Point Selection Criterion - #3

- Select grid points where scaled Q criterion (Q_s) is >= to 1
- Perform vortex core profiling at the selected grid points
- Display the core radius as a contour plot

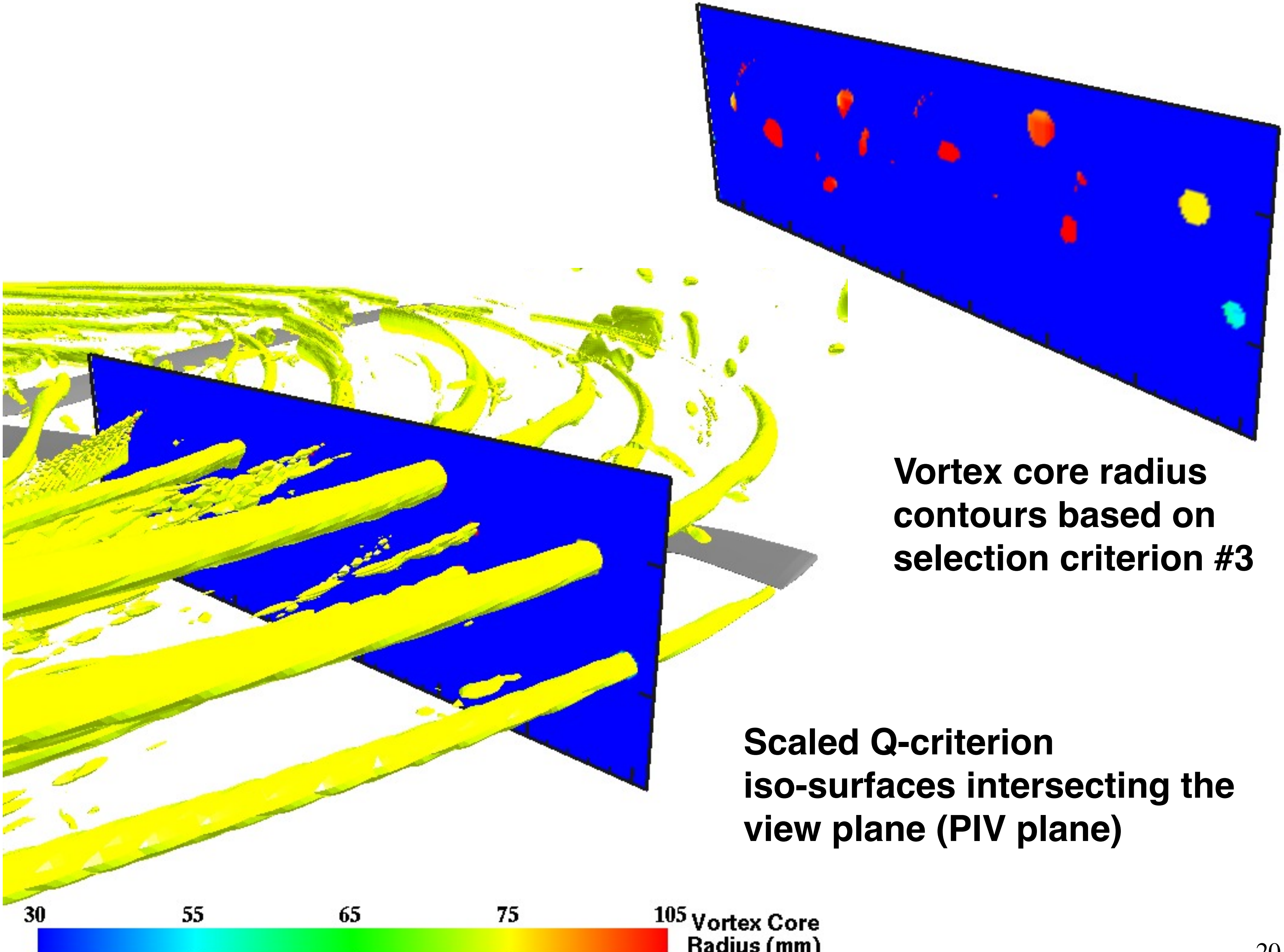


Scaled Q criterion contours



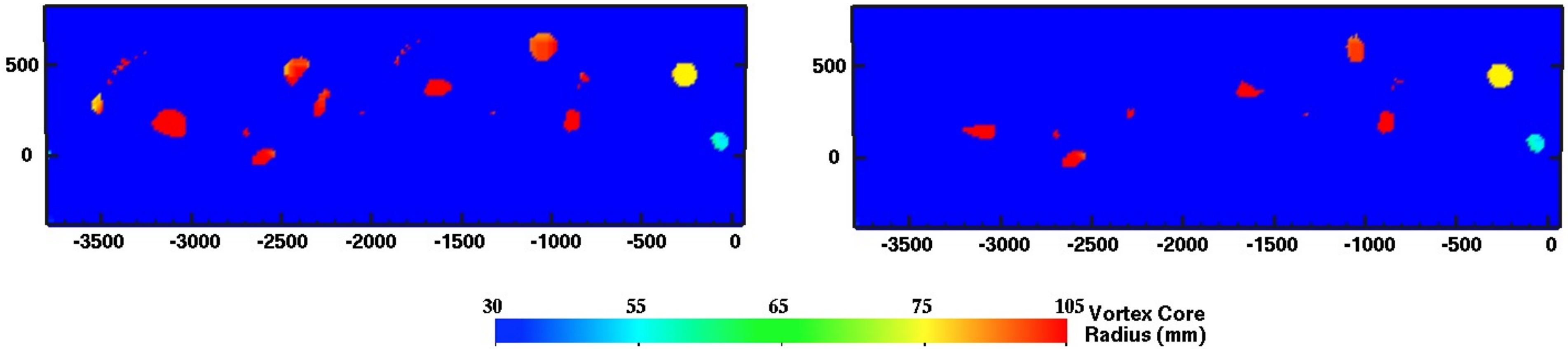
Vortex core radius contours

➢ A better depiction of each vortex core. However, some profiling locations are not near a vortex core center.

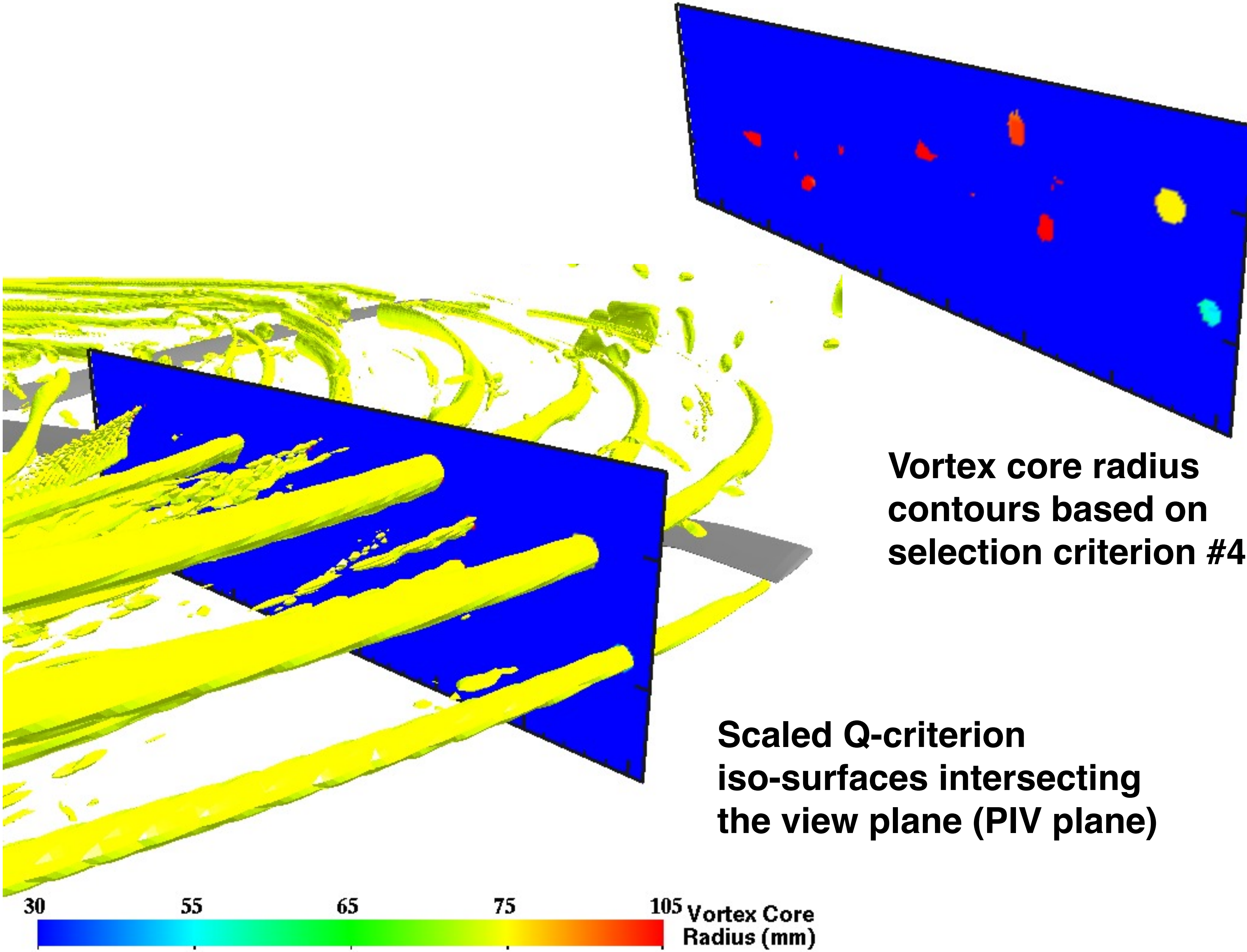

Vortex core radius
contours based on
selection criterion #3
Scaled Q-criterion
iso-surfaces intersecting the
view plane (PIV plane)
30
55
65
75
105
Vortex Core
Radius (mm)

Grid Point Selection Criterion - #4

- Select grid points where scaled Q criterion (Q_s) is >= to 1
- Further down select grid points with a high velocity variation
- Perform vortex core profiling at the selected grid points
- Display the core radius as a contour plot



- **A concise representation of vortex core attributes (centers and strengths)**


Vortex core radius
contours based on
selection criterion #4
Scaled Q-criterion
iso-surfaces intersecting
the view plane (PIV plane)
30
55
65
75
105
Vortex Core
Radius (mm)

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Summary - Grid Selection Criteria

- Construct a *view plane* to represent the experimental Particle Image Velocimetry (PIV) plane using a Cartesian grid

- Automatically extract vortex core strengths on the view plane

  - **Automatically select a set of grid points on the view plane to extract the vortex core radius using one of the following criteria:**

#1: Select all grid points in the view plane

#2: Select grid points where vorticity magnitude is above a threshold value

#3: Select grid points where scaled Q criterion >= to 1

#4: Select grid points where scaled Q criterion >= to 1 and with a high velocity variation

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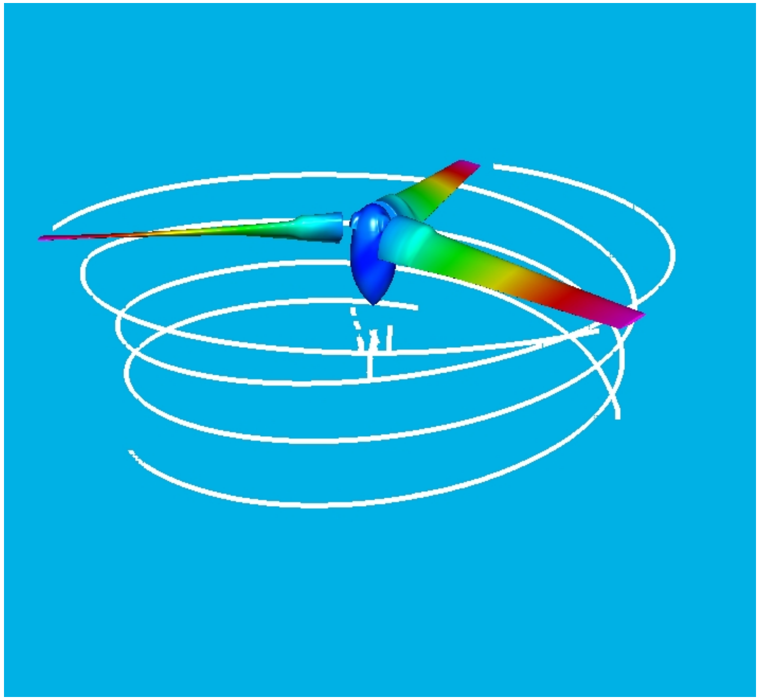
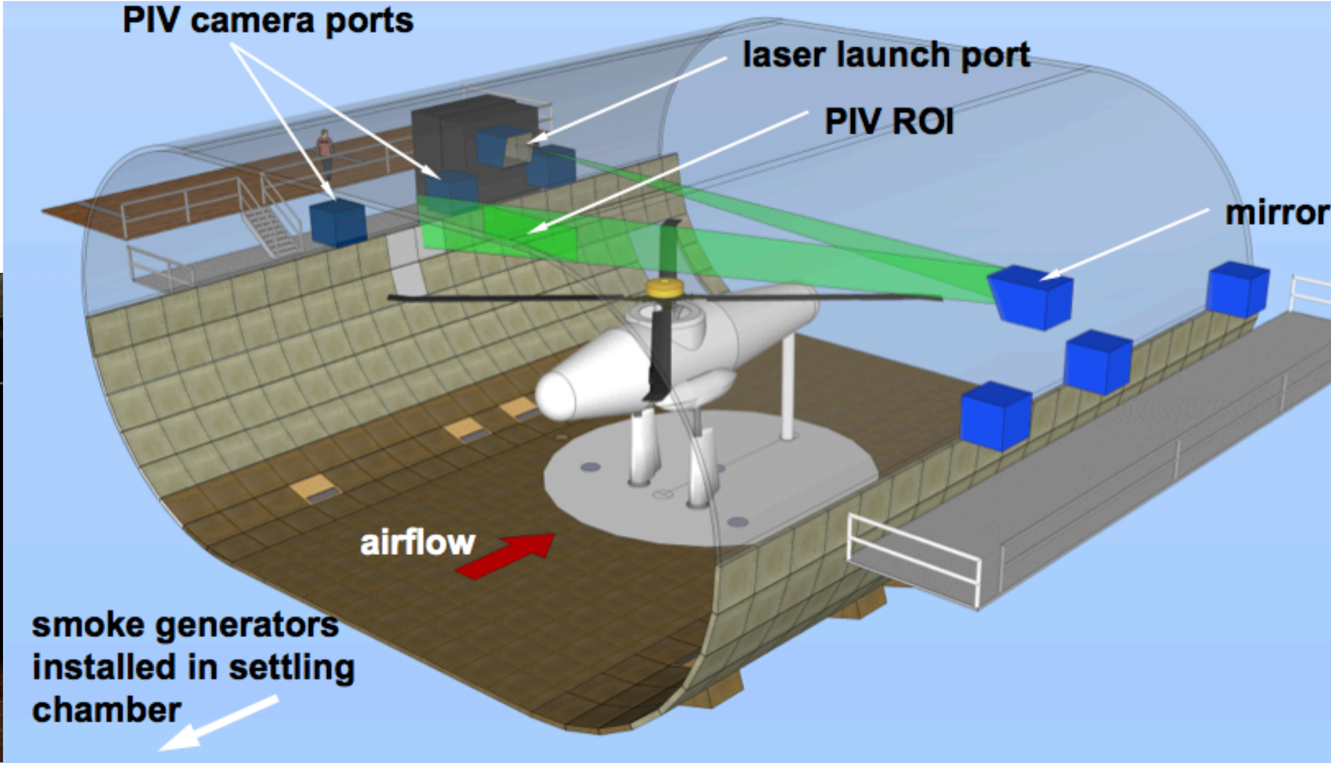


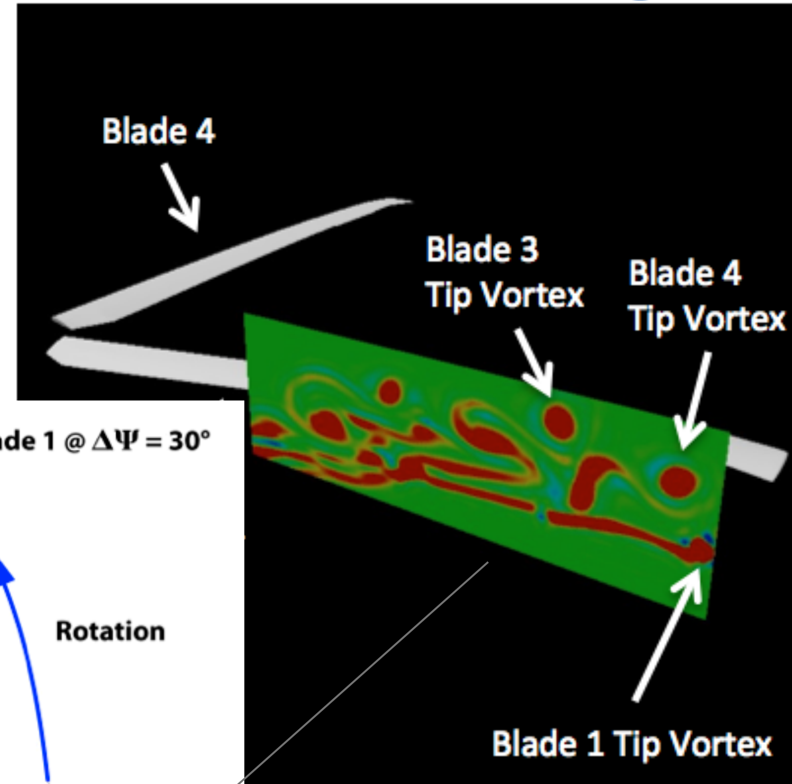
Results

- UH-60A rotor system from a PIV experiment run
- Run 73:   Advance ratio=0.15   Tip Mach number=0.65

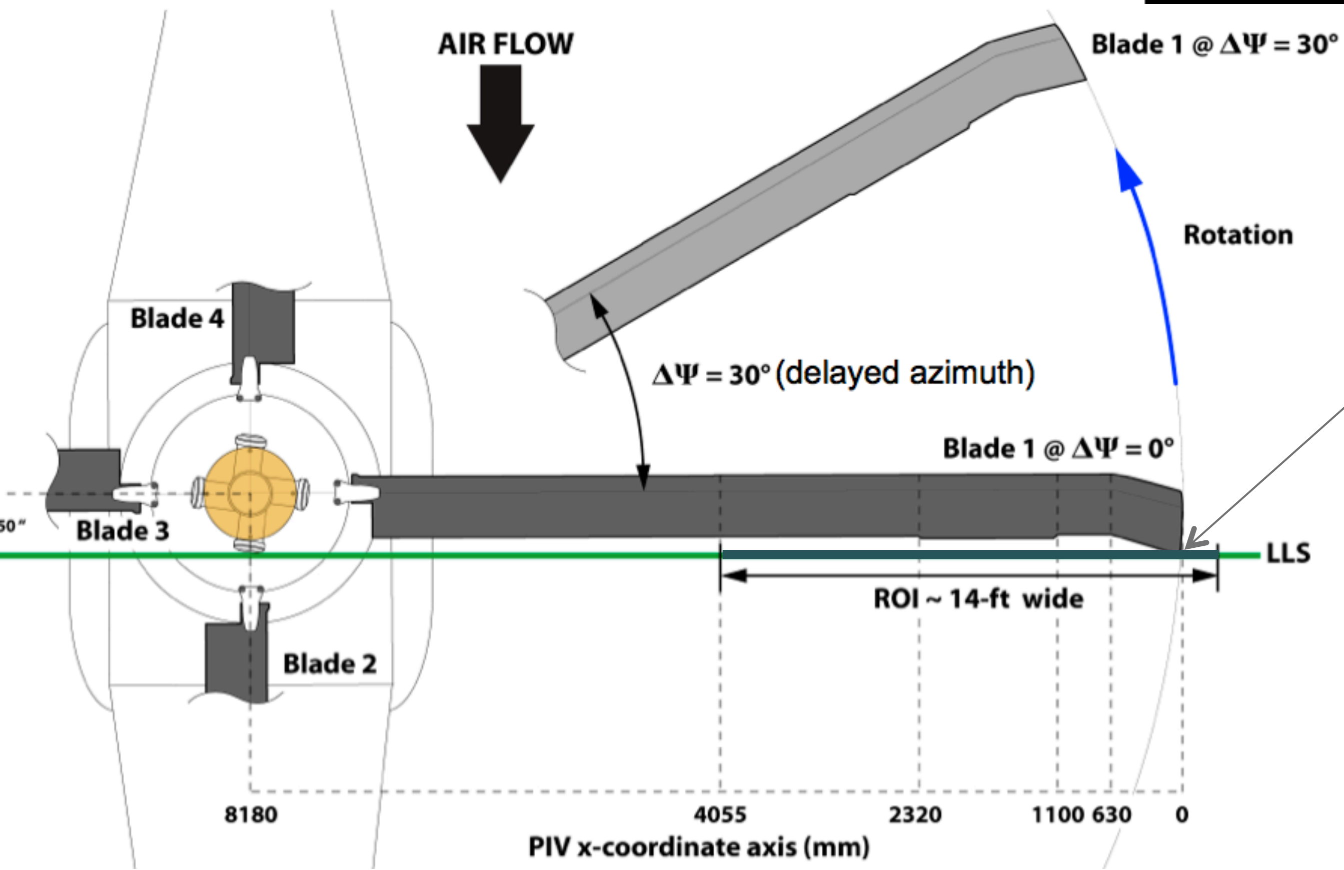


A PIV system in the National Full-Scale Aerodynamics Complex: 40 by 80-ft Wind Tunnel for UH-60A airloads test [Wadcock et al. '11, Yamauchi et al. '12]

Blade Position for PIV Measurements

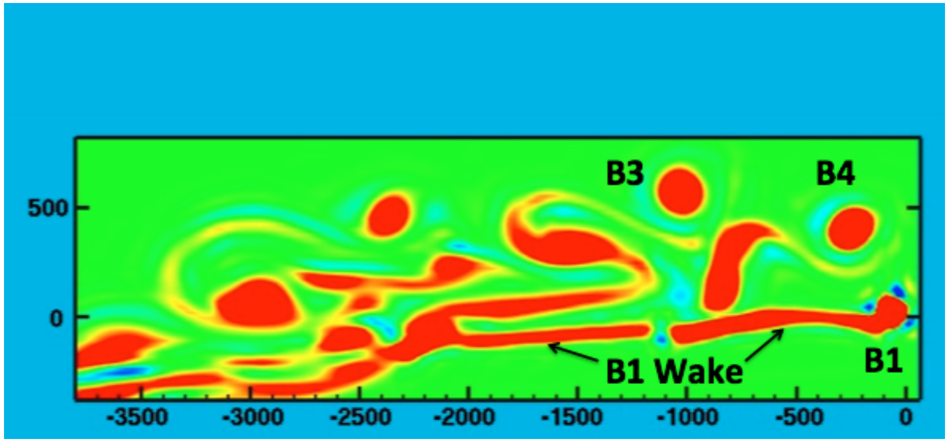


CFD

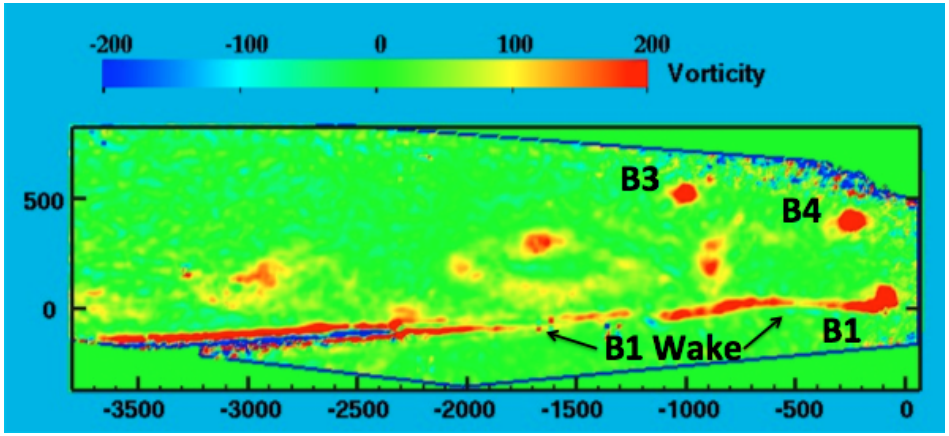


Experiment

Comparison of CFD and PIV Results



CFD



PIV

A comparison of vortex positions between computation and experiment for the blade 1 vortex (B1), blade 3 vortex (B3), and blade 4 vortex (B4)

- **The computed and measured wake positions are generally in good agreement**
- **The computed flow features are more diffuse due to numerical diffusion and coarse grid resolution**

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Case Study #1
Grid resolution study

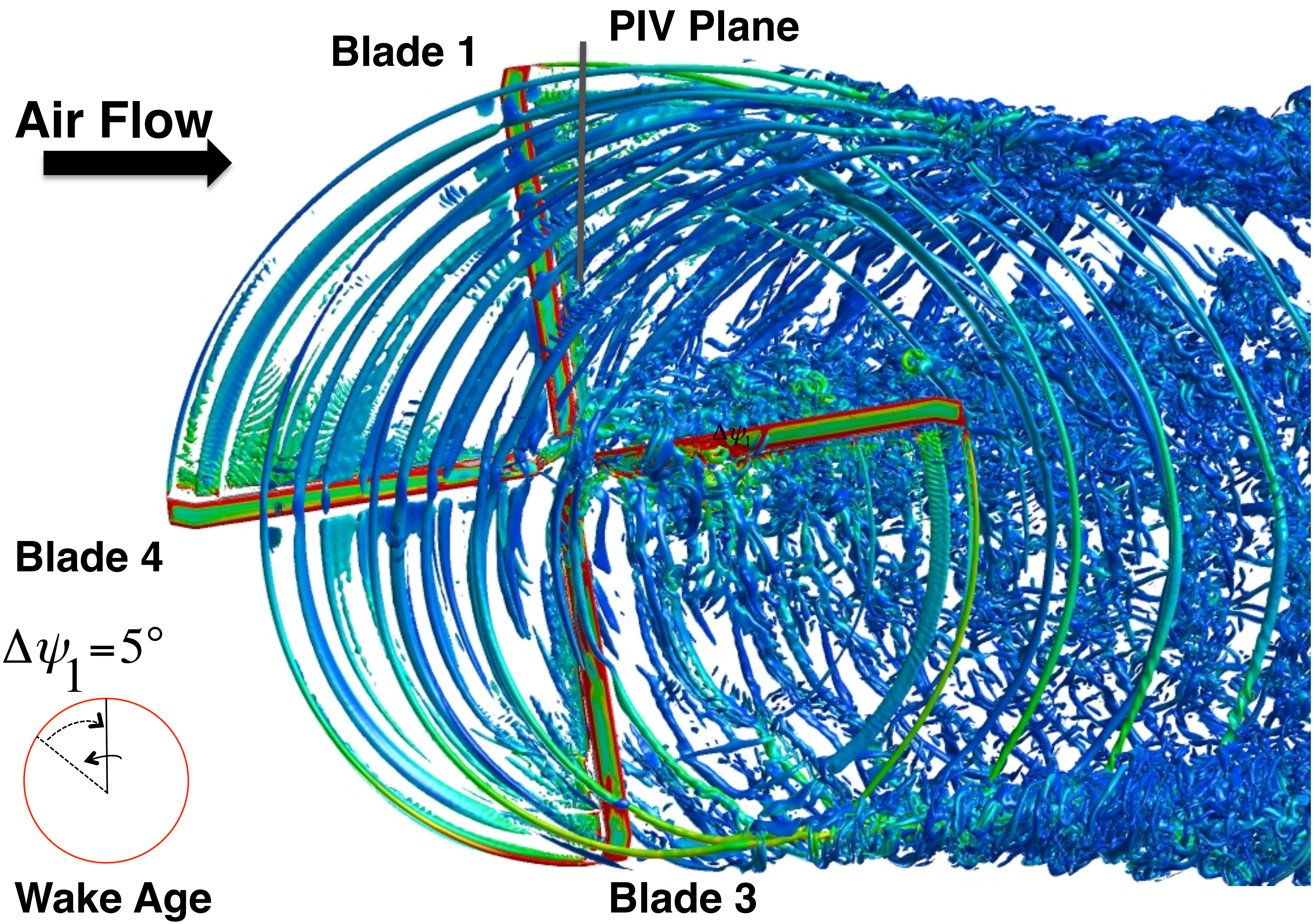
- **Isolated rotor system in free air, with flow conditions taken from Run 73 of the UH-60 Wind Tunnel PIV experiment**

- **Two grid systems: non-adaptive and Adaptive Mesh Refinement (AMR)**

Gridding System	Number of Grids	Total Grid Points	L1 Spacing
Non-adaptive	124	329 million	0.05 Ctip
Adaptive	12,239	725 million	0.10, 0.05, 0.025 Ctip

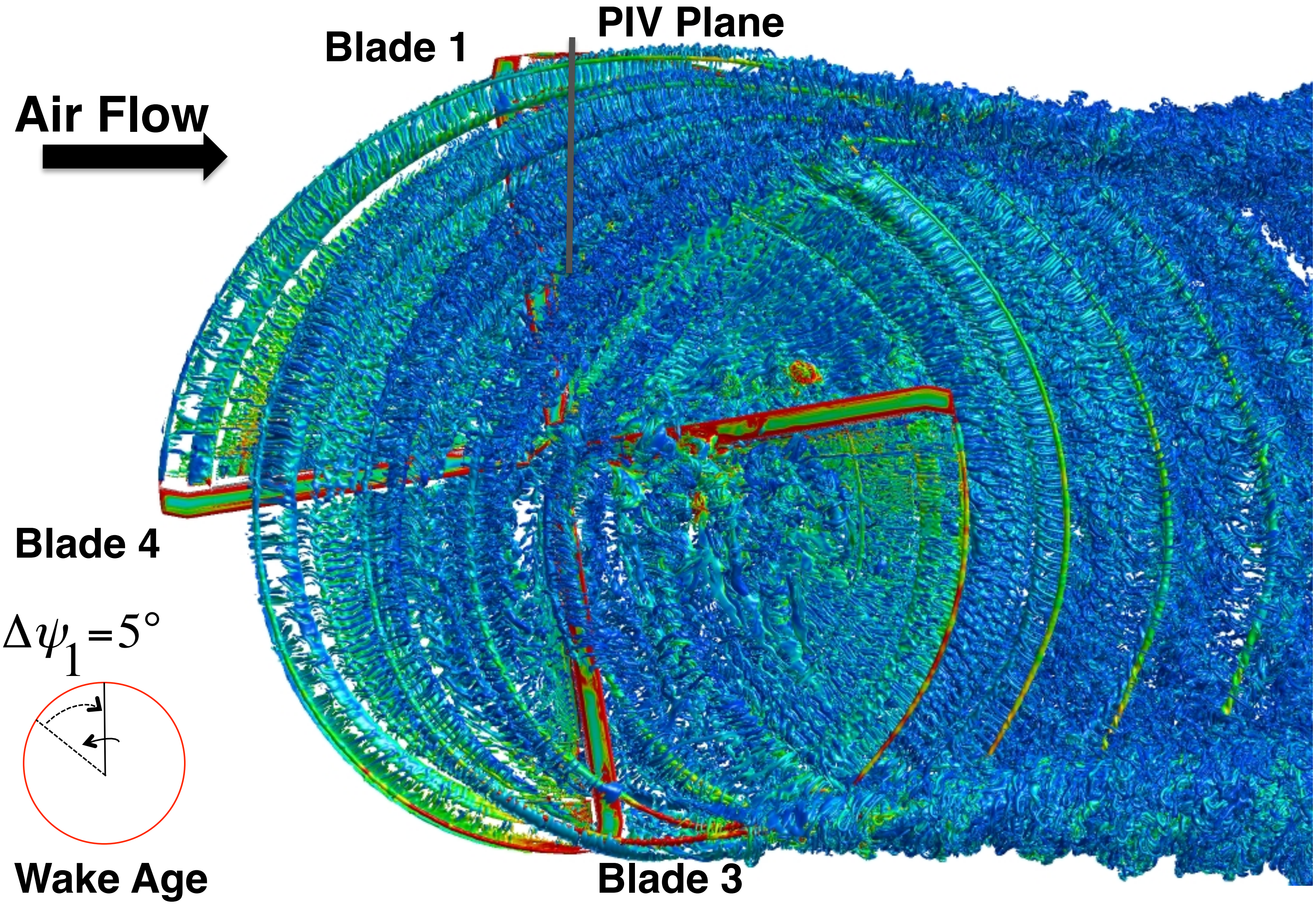
Ctip = chord spacing at blade tip

Case Study #1 – non-Adaptive Grids



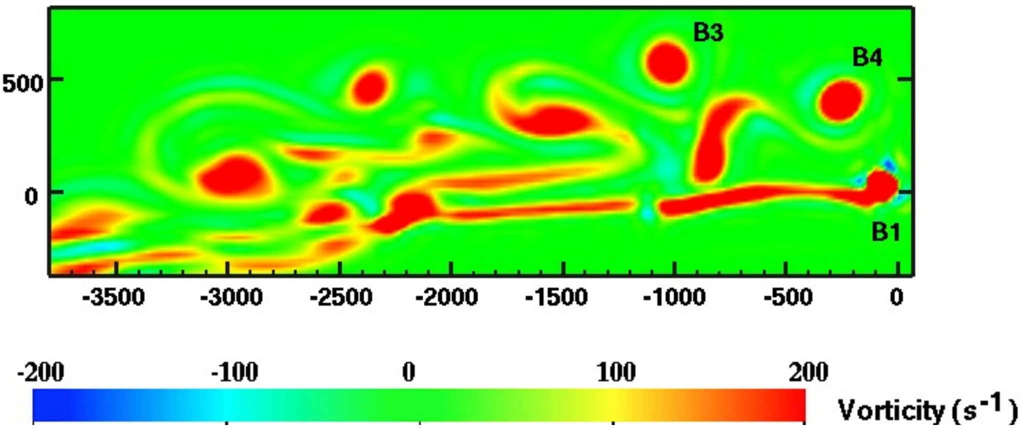
Q-criterion iso-surfaces colored by vorticity magnitude

Case Study #1 – AMR Grids



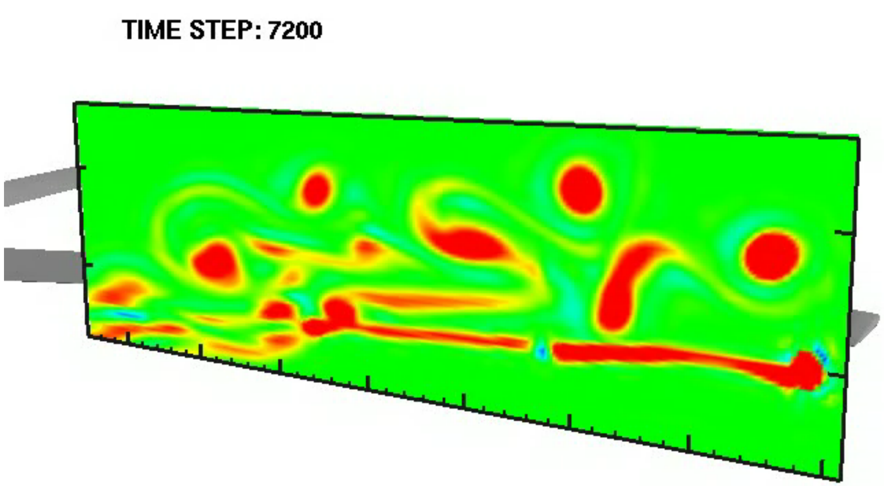
Q-criterion iso-surfaces colored by vorticity magnitude

Results – Case Study #1
Non-Adaptive Grids



Vorticity magnitude contours

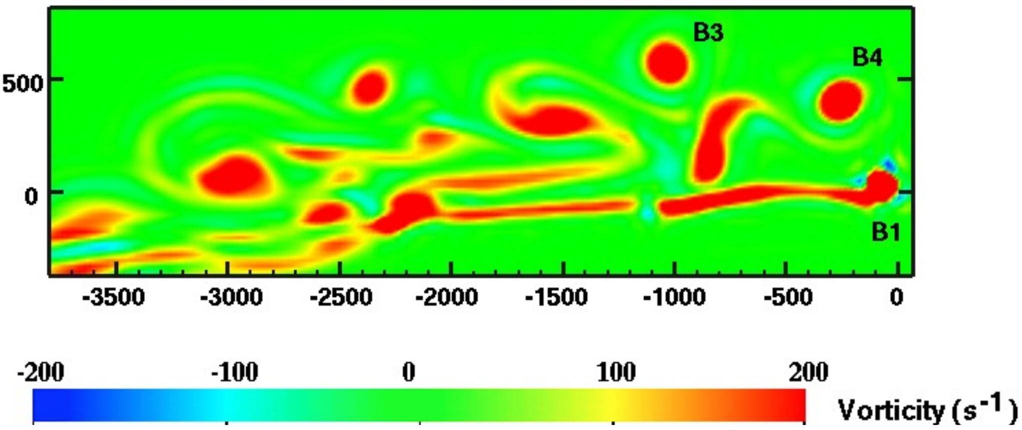
Run 73, M_{tip} = 0.65, μ = 0.15



Animation:

Trajectory of the vortices over one blade revolution

Results – Case Study #1
Non-Adaptive Grids

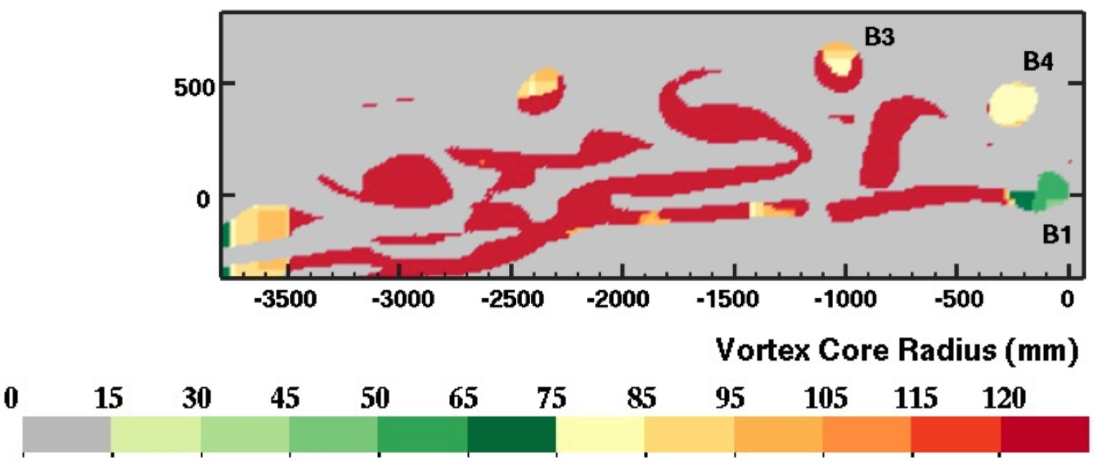


Vorticity magnitude contours

Run 73, $M_{tip} = 0.65$, $\mu = 0.15$

$$\Delta\psi_1 = 5^\circ$$

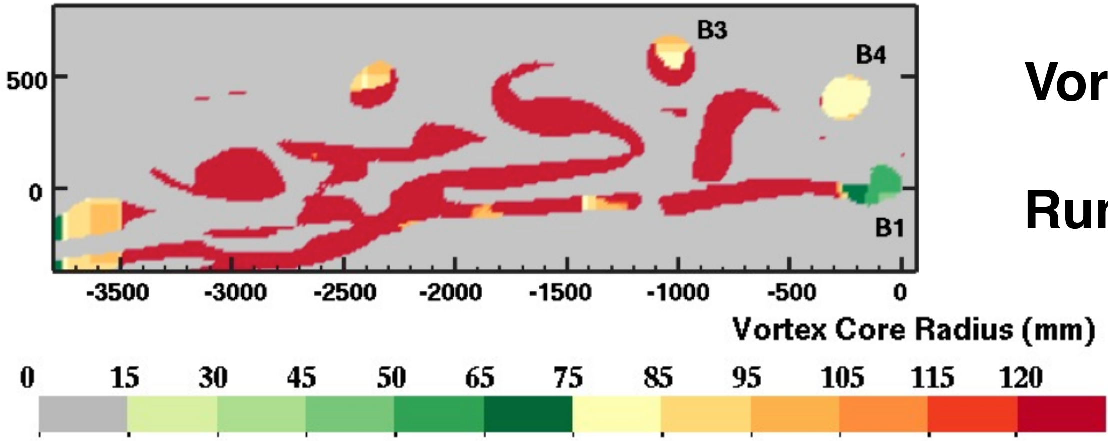
Vortex core radius contours



Selection Criterion: #2

Core radii calculated for grids points where vorticity magnitude > 64 s^{-1}

Results – Case Study #1
Non-Adaptive Grids

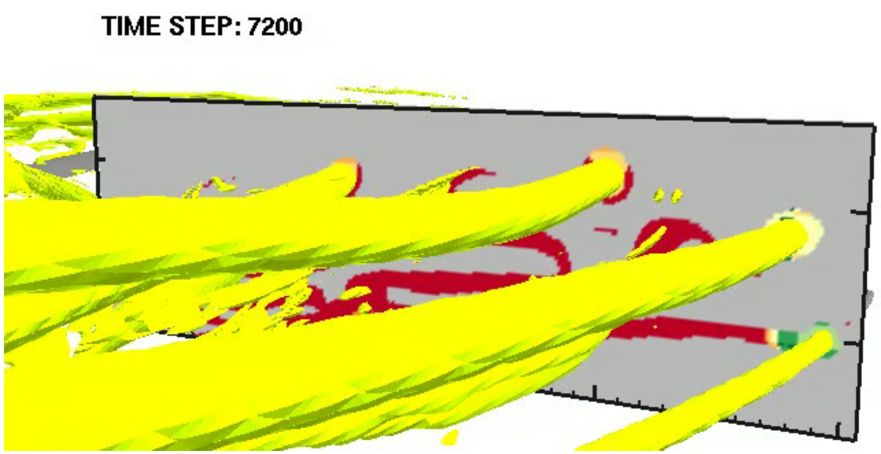


Vortex core radius contours

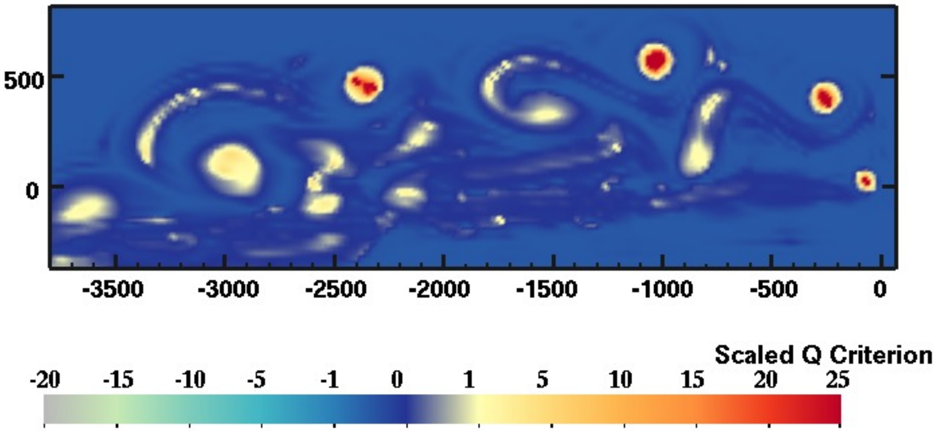
Run 73, M_{tip} = 0.65, μ = 0.15

Animation:

Scaled Q-criterion isosurfaces intersecting the view plane colored by vortex core radius



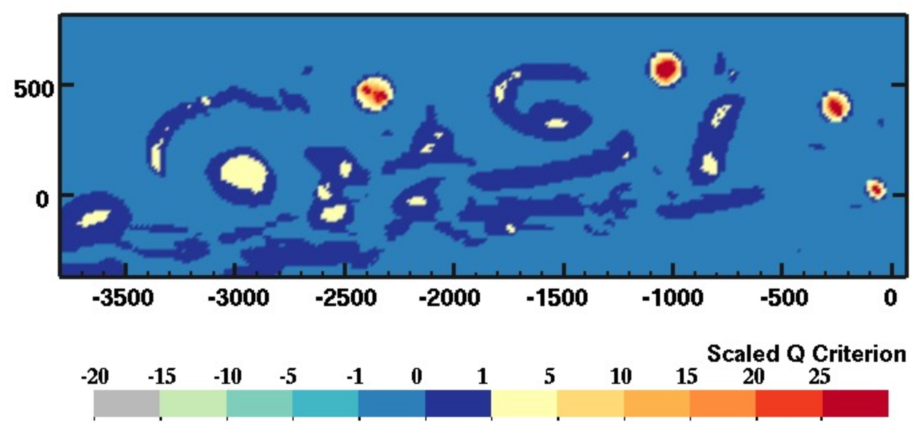
Results – Case Study #1
Non-Adaptive Grids



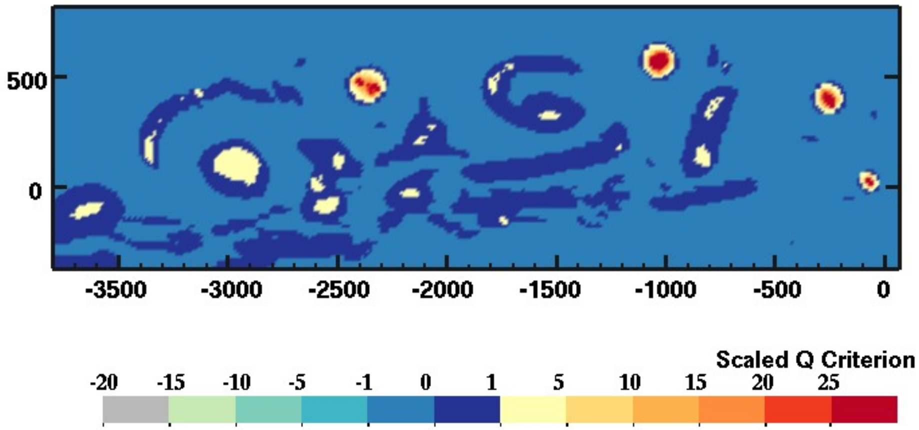
Scaled Q criterion (Q_s)

Run 73, $M_{tip} = 0.65$, $\mu = 0.15$

Banded color map gives a better delineation of the vortex core boundary

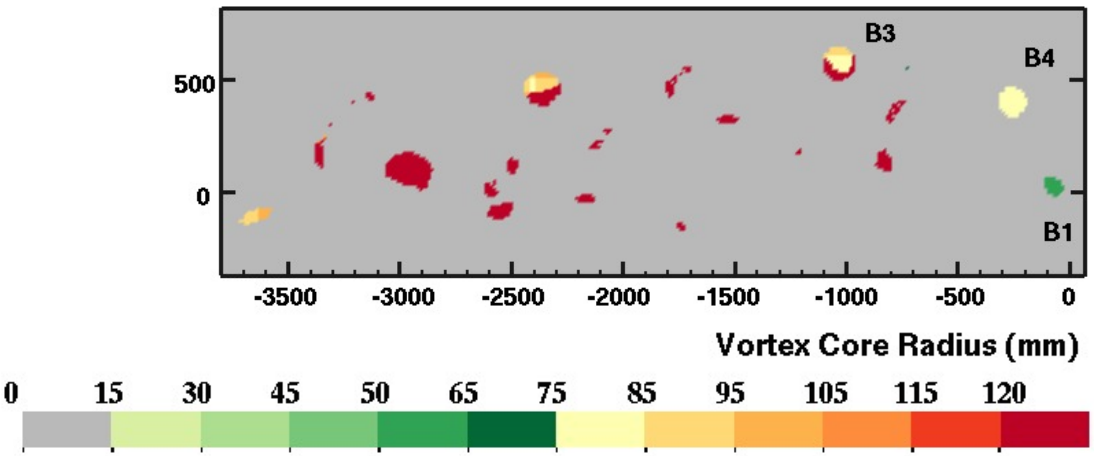


Results – Case Study #1
Non-Adaptive Grids



Scaled Q criterion (Q_s)

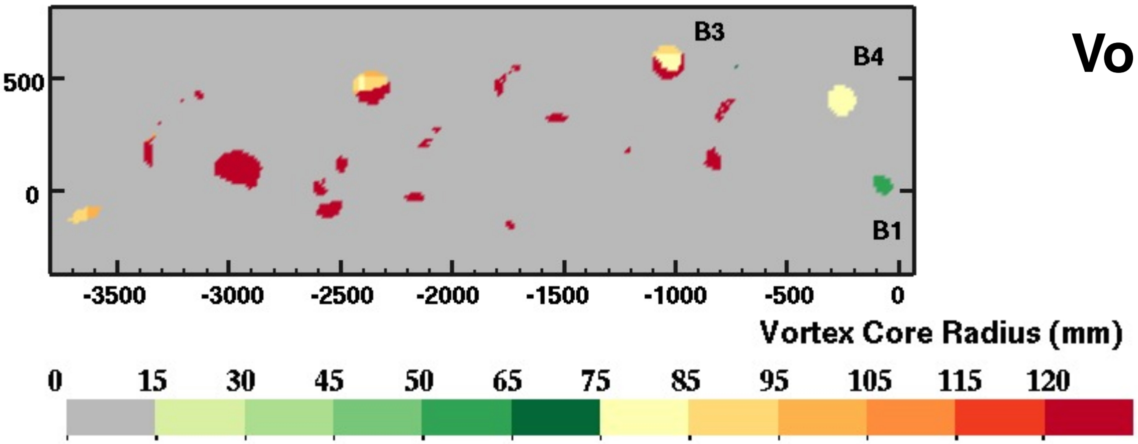
Vortex core radius contours



Selection Criterion: #3

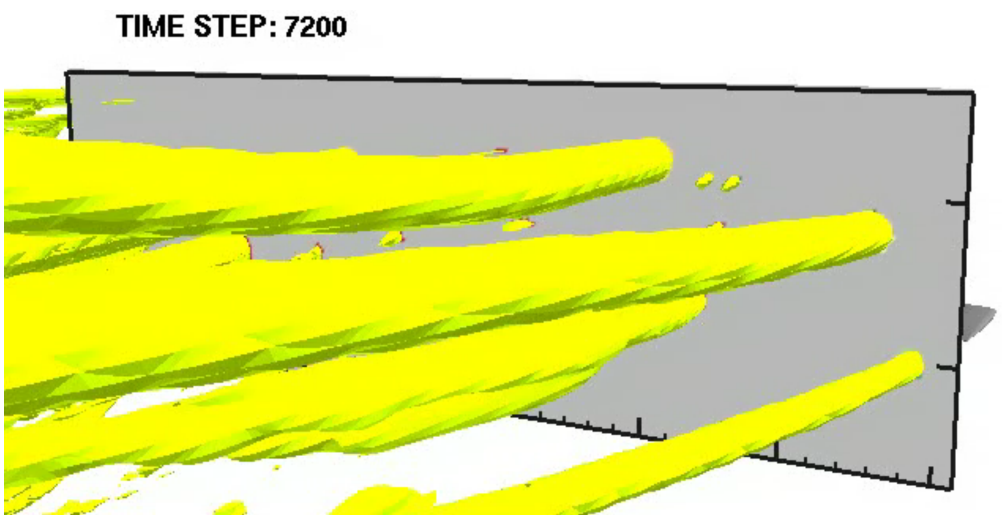
Core radii calculated for grids points where Q_s>=1

Results – Case Study #1
Non-Adaptive Grids

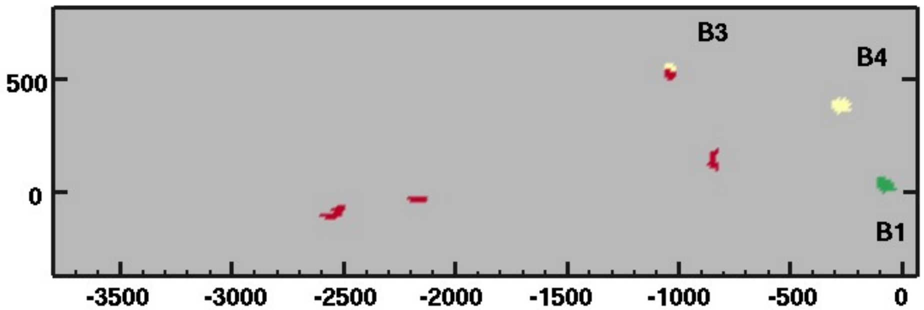


Vortex core radius contours

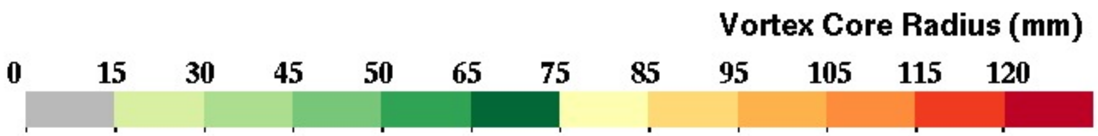
Scaled Q-criterion isosurfaces intersecting the view plane colored by vortex core radius



Results – Case Study #1
Non-Adaptive Grids

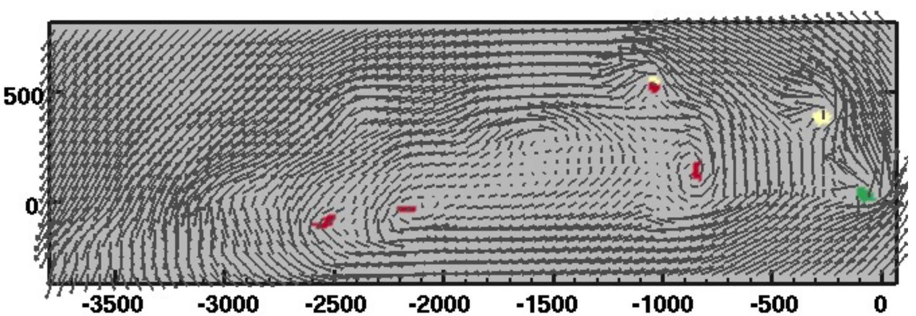


Vortex core radius contours



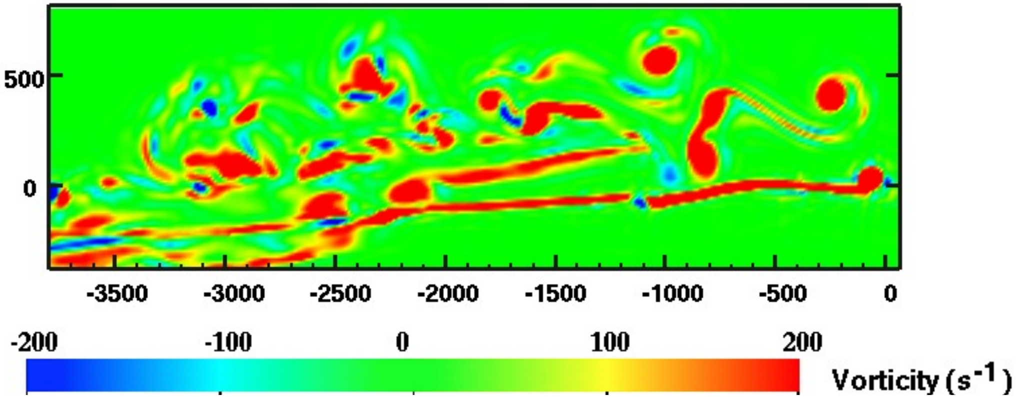
Selection Criterion: #4

Core radii calculated for grid points where Qs>=1 and with high velocity variation



- **Concise representation of vortex core size and position**

Results – Case Study #1
AMR Grids

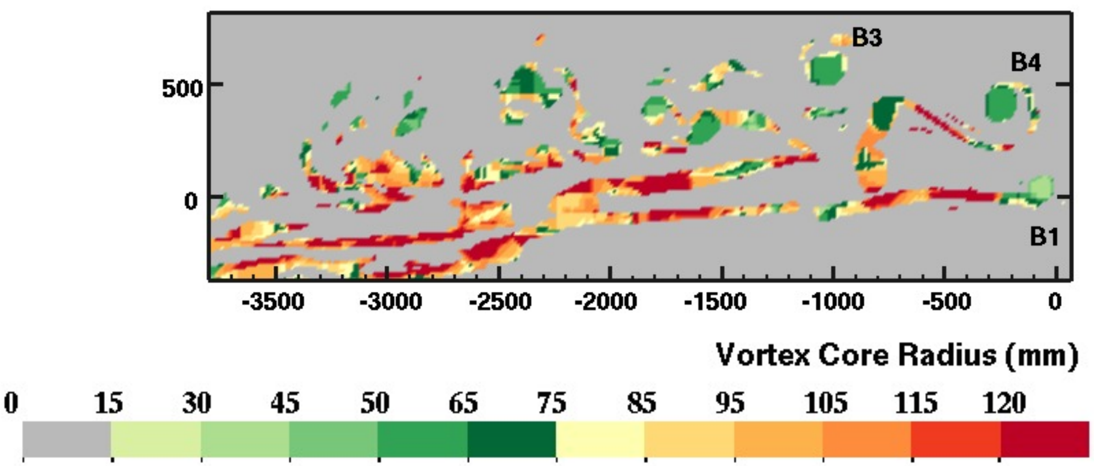


Vorticity magnitude contours

Run 73, $M_{tip} = 0.65$, $\mu = 0.15$

$$\Delta\psi_1 = 5°$$

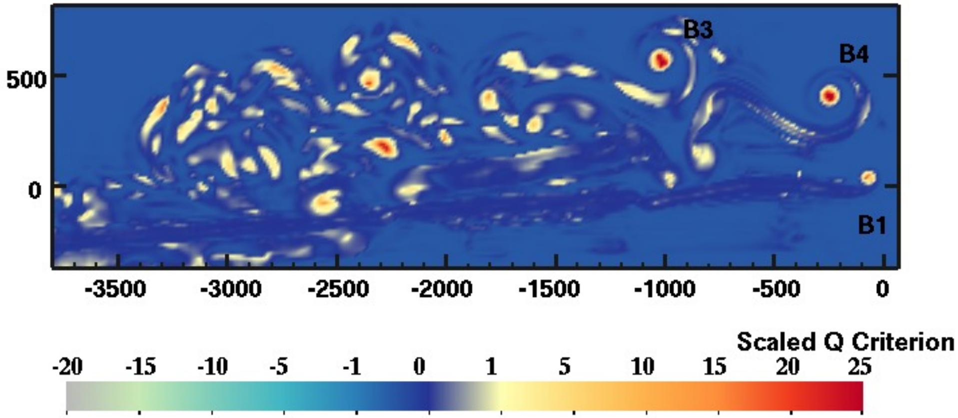
Vortex core radius contours



Selection Criterion: #2

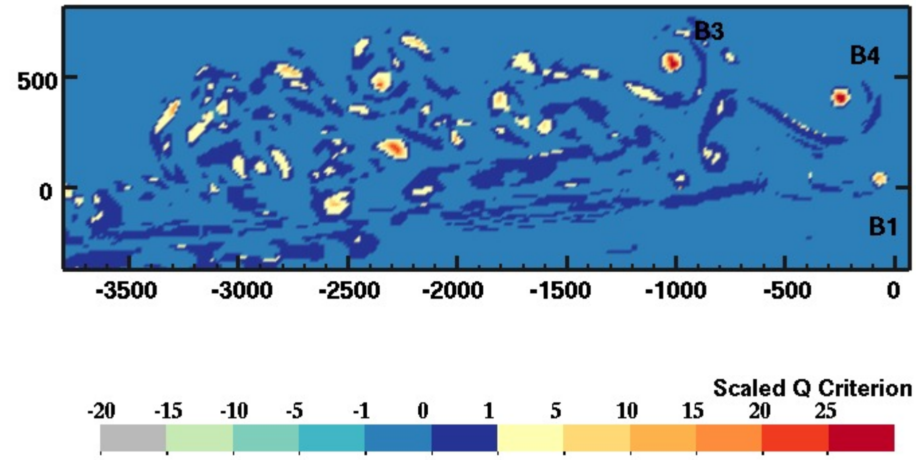
Core radii calculated for grids points where vorticity magnitude > 64 s^{-1}

Results – Case Study #1
AMR Grids

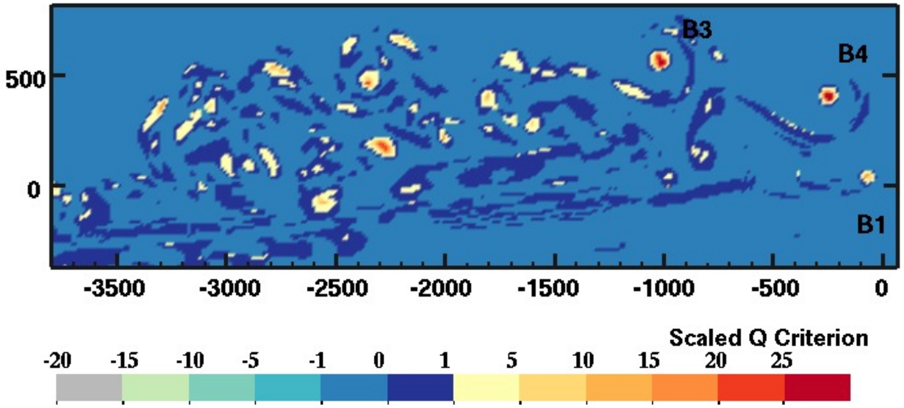


Scaled Q criterion (Q_s)

Banded color map gives a better delineation of the vortex core boundary

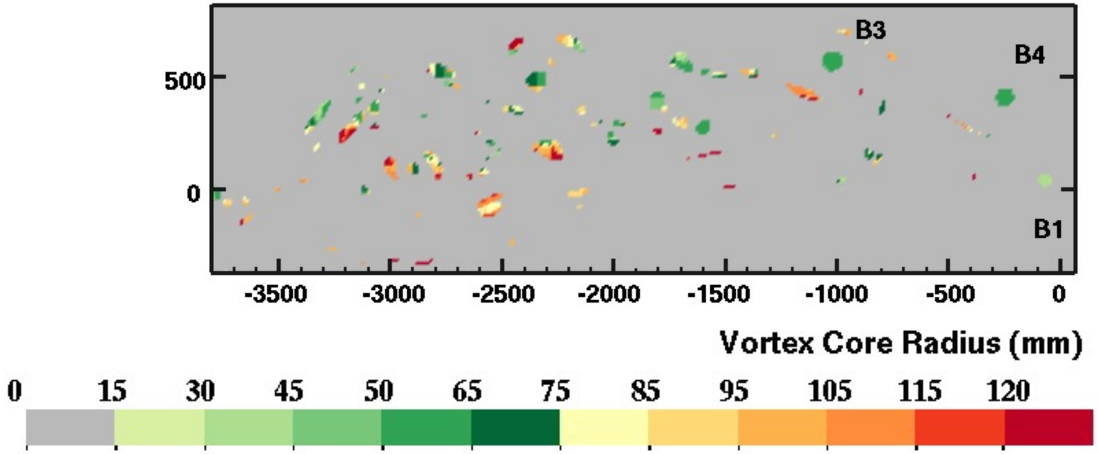


Results – Case Study #1
AMR Grids



Scaled Q criterion (Q_s)

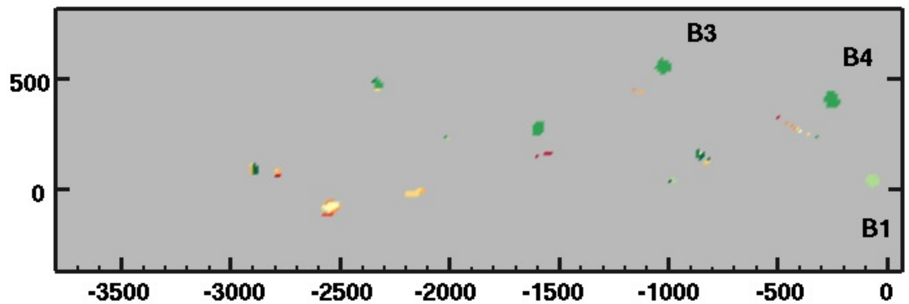
Vortex core radius contours



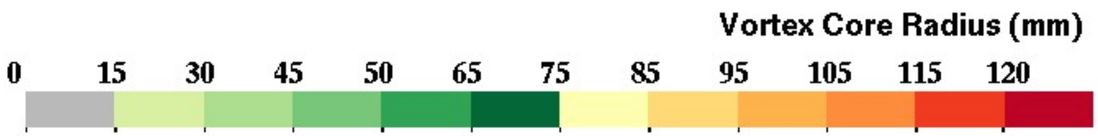
Selection Criterion: #3

Core radii calculated for grids points where Q_s>=1

Results – Case Study #1
AMR Grids

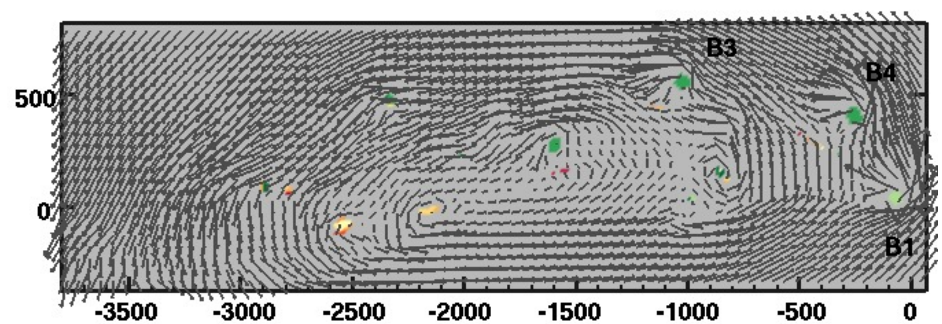


Vortex core radius contours



Selection Criterion: #4

Core radii calculated for grid points where Qs>=1 and with high velocity variation



- ➢ **Concise representation of vortex core size and position**

Ames Research Center

Case Study #2
Wind tunnel wall effect study

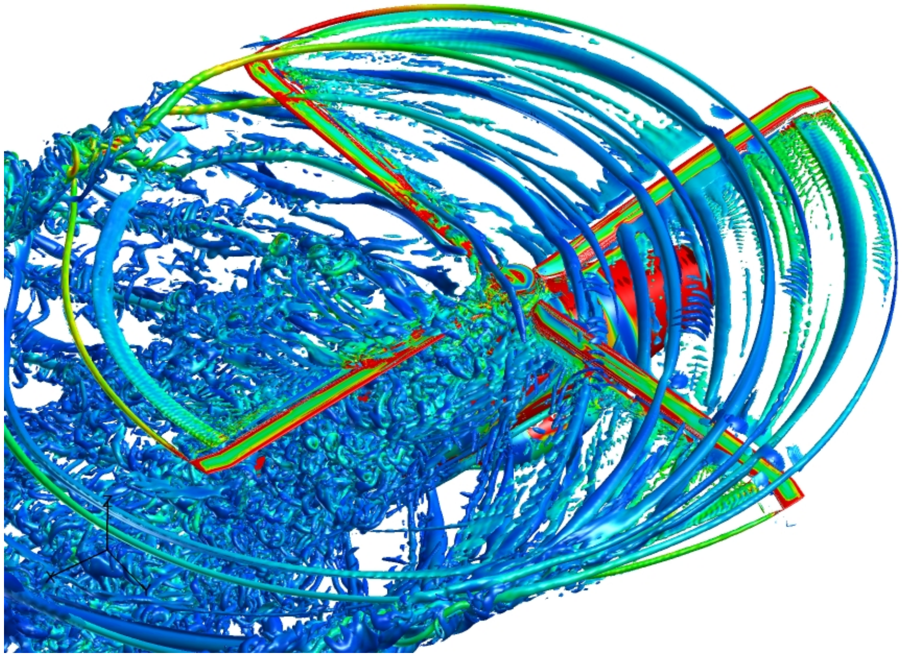
- Similar to case #1 except the fuselage is included. Flow conditions taken from Run 73 of the UH-60 Wind Tunnel PIV experiment

- Two flow conditions: Free air and with wind tunnel walls modeled

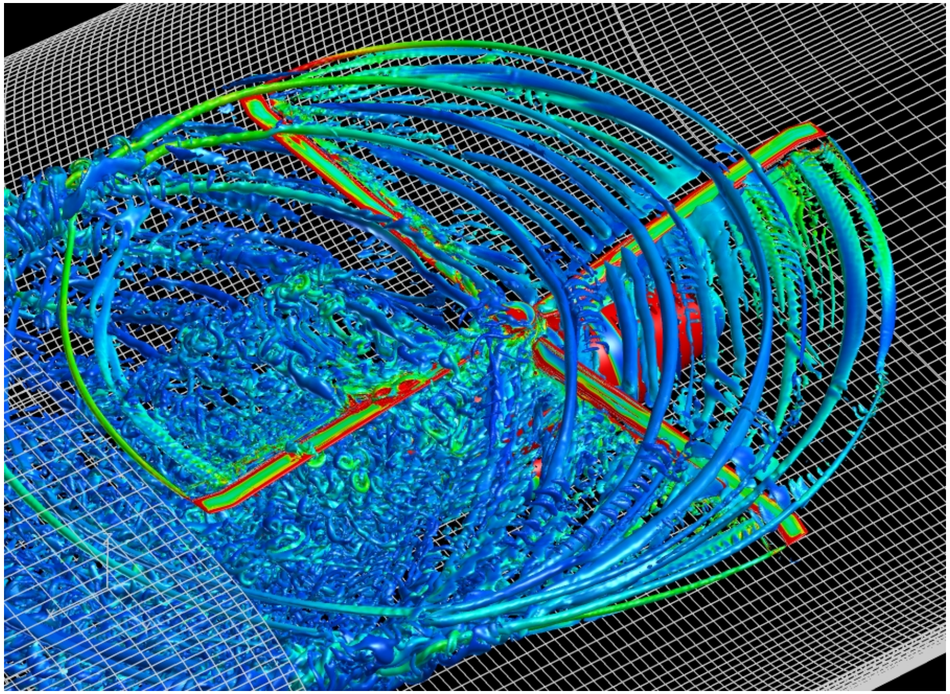
Gridding System	Number of Grids	Total Grid Points	L1 Spacing
Free Air	136	403 million	0.05 Ctip
Wind Tunnel Walls	36	299 million	0.05 Ctip

Ctip = chord spacing at blade tip

Case Study #2



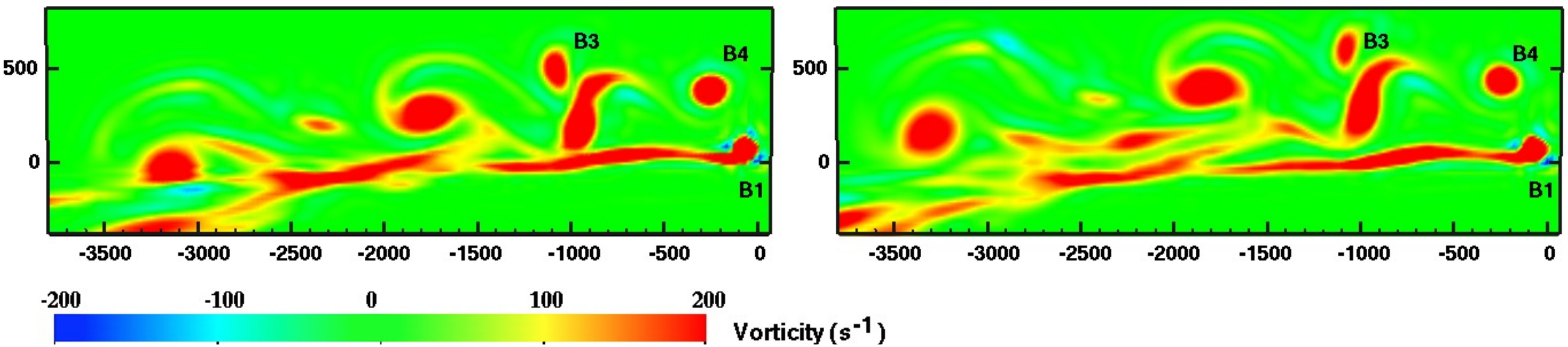
Free Air



With Wind Tunnel Walls

Q-criterion iso-surfaces colored by vorticity magnitude

Results - Case Study #2

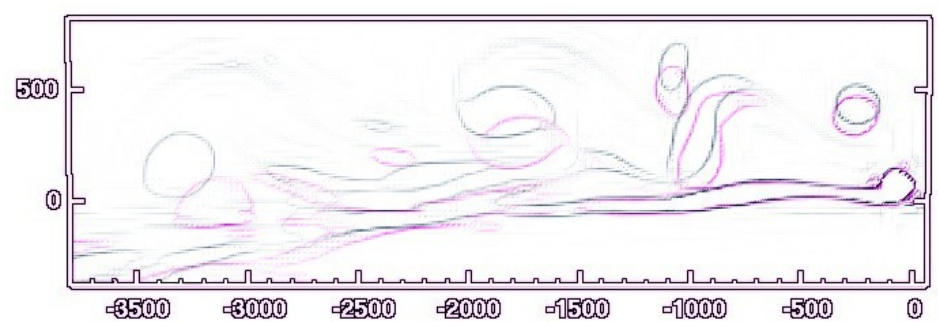


Free Air

With Wind Tunnel Walls

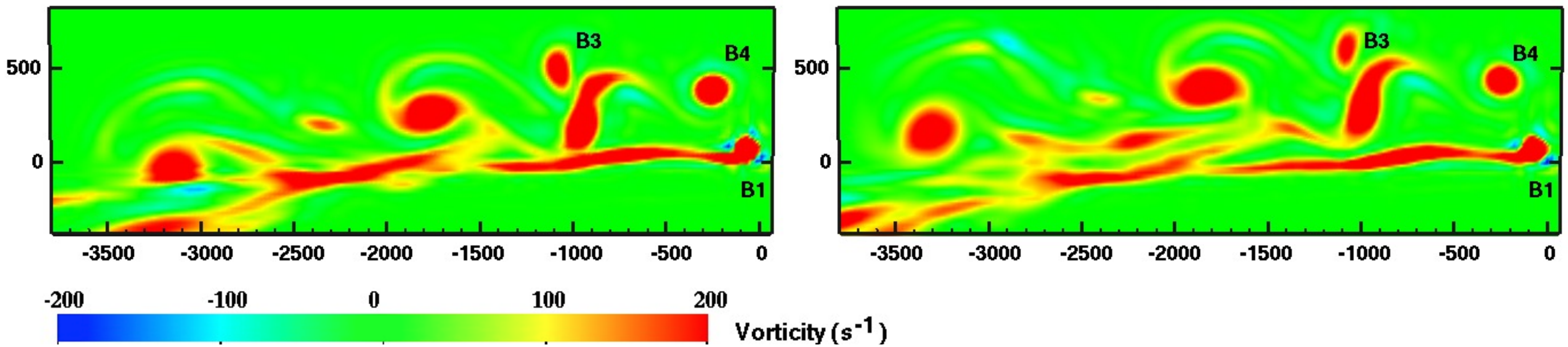
Vorticity magnitude contours

Run 73, M_{tip} = 0.65, μ = 0.15

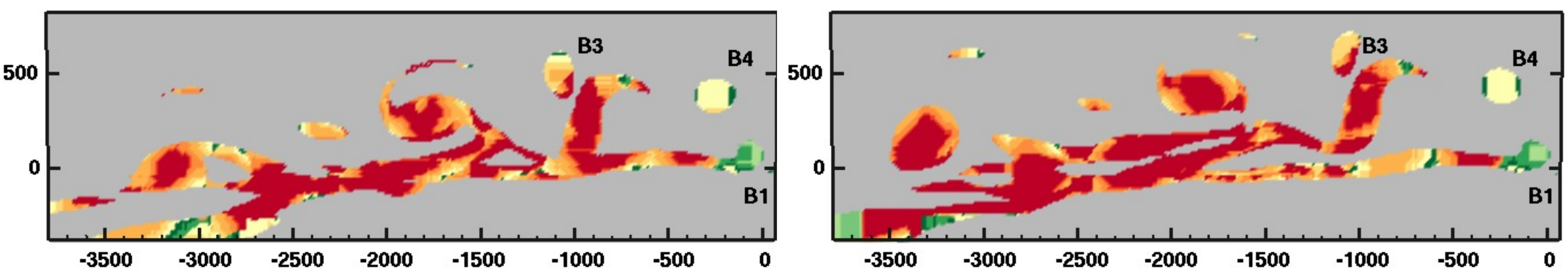


Free air simulation (magenta)
Wind tunnel walls simulation (black)

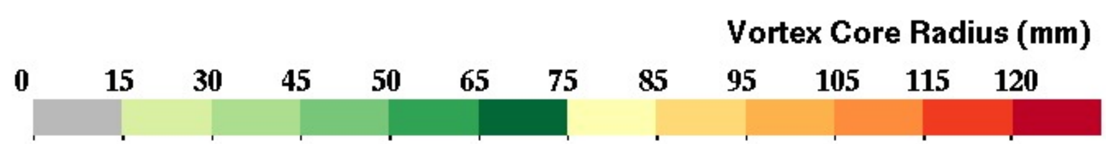
Results - Case Study #2



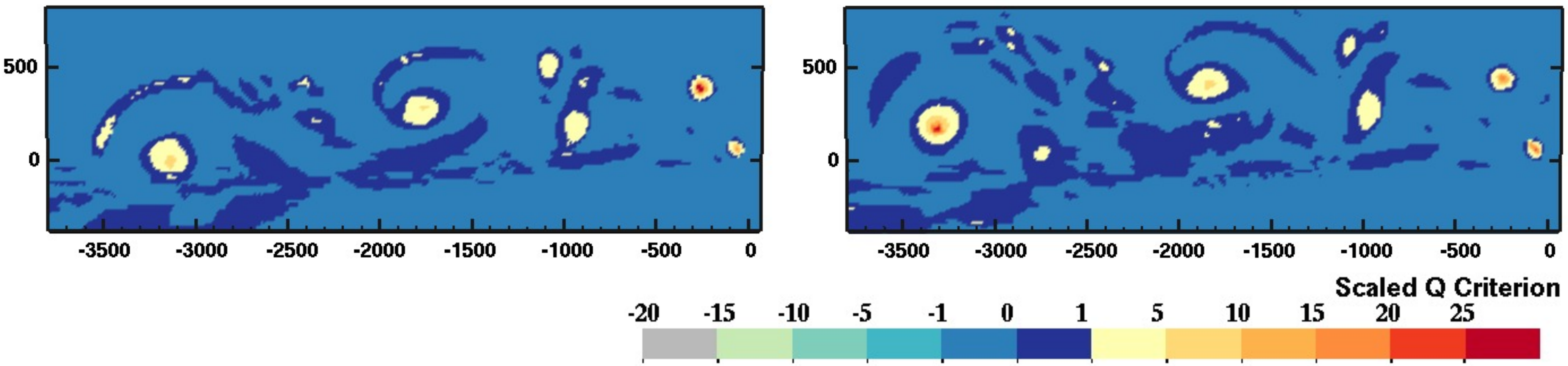
Free Air | **With Wind Tunnel Walls**



Selection Criterion #2:
Core radii calculated for grid points where ||Vort|| > 64 s^{-1}

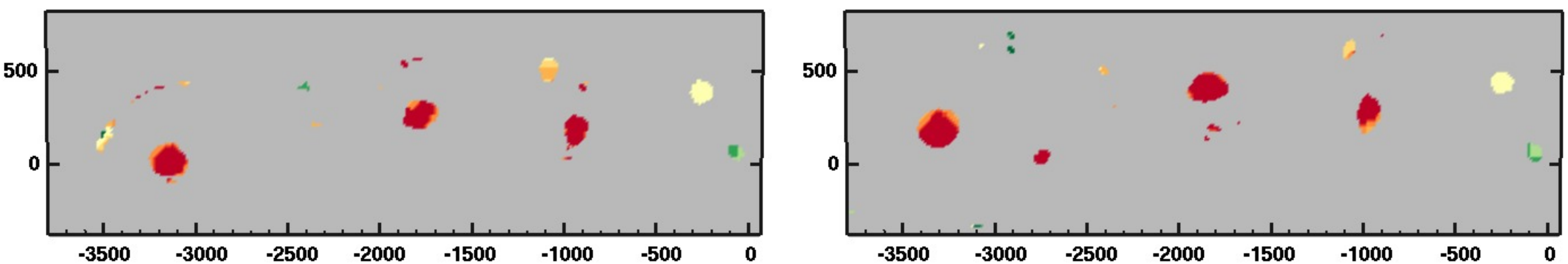


Results – Case Study #2

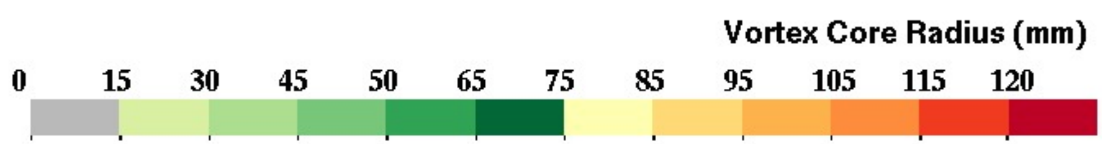


Free Air

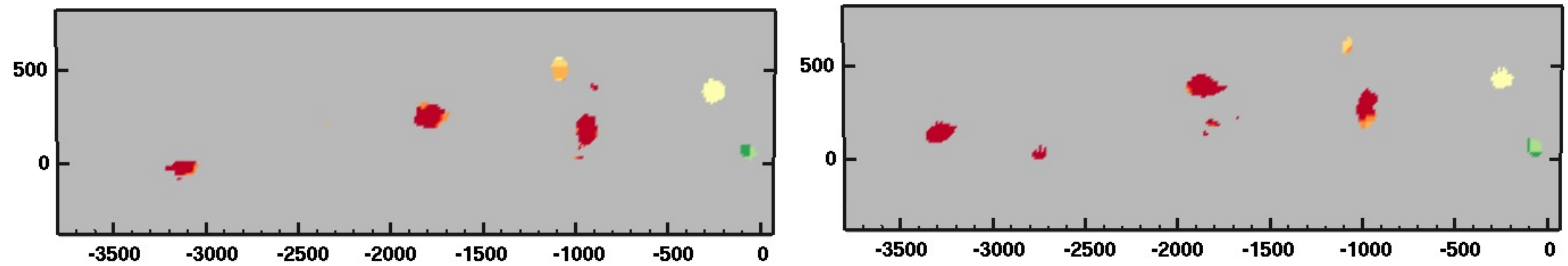
Wind Tunnel Walls



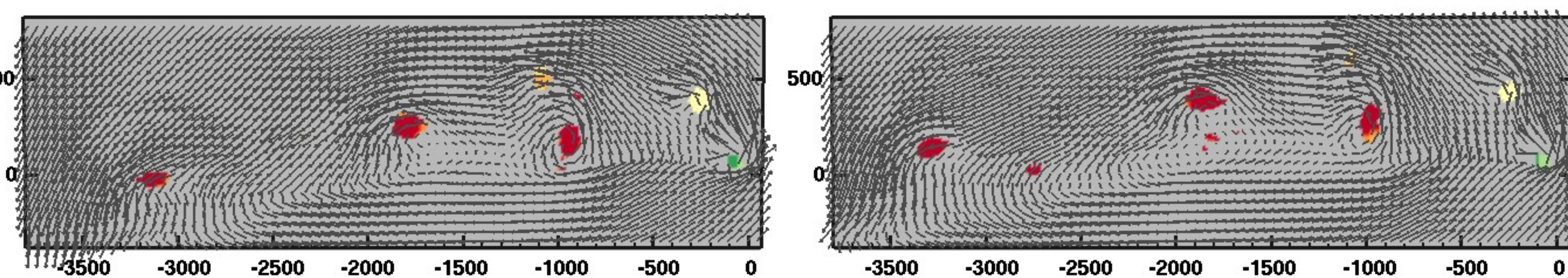
Selection Criterion #3: Core radii calculated for grid points where Q_s>=1



Results – Case Study #2

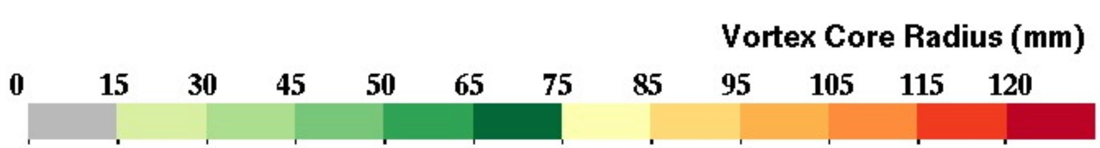


Free Air **Wind Tunnel Walls**



Selection Criterion: #4

Core radii calculated for grid points where Q_s>=1 and with high velocity variation



Conclusions

An automated approach for extracting and quantifying rotor tip strengths is presented

Several criteria are evaluated for selecting grid points to perform vortex core profiling and core radius calculation

New color map scheme based on vortex core radius is presented

New scheme provides concise presentation of vortex core strength when compared to scalar quantities such as vorticity magnitude